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LABORATORY EVALUATION OF NO_x REDUCTION TECHNIQUES FOR REFINERY CO BOILERS

by

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16. ABSTRACT The report describes a laboratory test program to investigate NOx emissions from refinery CO boilers. The program had three major objectives: (1) to simulate in the laboratory a full-scale refinery CO boiler, (2) to investigate the effects of operational variables on NOx formation in the boiler furnace, and (3) to evaluate combustion modification techniques to reduce the NOx emissions. The laboratory model was shown to accurately represent combustion and NOx formation processes occurring in the full-scale boiler by comparing combustion products analyses over a range of operating conditions. The most significant operating variables influencing NOx formation in the CO boiler were found to be the ammonia level in the CO-gas and the burner stoichiometry. NOx reduction methods that were tested included combustion air staging, staged admission of fuel, fuel injection in the CO-gas, redesign of the fuel injectors, and burner throat redesign. The most effective NOx reduction technique was found to be combustion air staging. NOx formation in the CO boiler was reduced to zero (NOx emission equivalent to NOx entering with CO-gas) in the laboratory while maintaining acceptable (< 200 ppm) CO levels in the stack gas. While zero NOx formation will probably not be achievable in the field, substantial NOx reductions should be achievable under practical operating conditions.

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ABSTRACT

A laboratory test program was conducted to investigate NO_x emissions from refinery CO boilers. The program had the following three major objectives: (1) to simulate in the laboratory a full-scale refinery CO boiler, (2) to investigate the effects of operational variables on NO_x formation in the boiler furnace, and (3) to evaluate combustion modification techniques to reduce the NO_x emissions.

The laboratory model was shown to accurately represent combustion and NO_x formation processes occurring in the full-scale boiler by comparison of combustion products analyses over a range of operating conditions. The most significant operating variables influencing NO_x formation in the CO boiler were found to be the ammonia level in the CO-gas and the burner stoichiometry. Oxidation of ammonia to NO_x was found to account for most of the NO_x formed in the boiler furnace. The data also showed that NO_x contained in the CO-gas is partially destroyed in passing through the CO boiler.

NO_x reduction methods that were tested included combustion air staging, staged admission of fuel, fuel injection in the CO-gas, redesign of the fuel injectors, and burner throat redesign. The most effective NO_x reduction technique was found to be combustion air staging. Part of the combustion air was diverted away from the burner and added downstream in the furnace to complete the combustion process. This reduced the oxygen level in the high-temperature burner zone of the furnace and thus reduced oxidation of ammonia to NO_x. The effectiveness of combustion air staging in achieving NO_x reduction without simultaneously increasing the CO level leaving the boiler was found to be strongly dependent on the placement of the second-stage combustion air.

NO_x formation in the CO boiler was reduced to zero (NO_x emission equivalent to NO_x entering with CO-gas) in the laboratory while maintaining acceptable (<200 ppm) CO levels in the stack gas. While zero NO_x formation will probably not be achievable in the field where conditions are far less controllable, substantial NO_x reductions should be achievable under practical operating conditions.

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The support of the South Coast Air Quality Management District of California is also acknowledged. This organization has firmly supported a long-standing effort by Powerine and KVB to develop an improved understanding of CO boiler NO_x emissions and to devise optimum technical control methods.

Finally, the authors wish to acknowledge valuable contributions to the program by S. C. Hunter and L. J. Muzio, both of KVB. Hunter provided important inputs to overall program guidance, and Muzio made valuable technical contributions to the program.

Limitations on Application of Reported Data

The pollutant emission data contained in this report pertain to a laboratory model of a refinery CO boiler. This data should not be used to estimate mean emissions from refinery CO boilers in general or to estimate emission reduction potentials of combustion modifications on refinery CO boilers until such modifications have been demonstrated on full-scale equipment.

SECTION 1.0

INTRODUCTION

Most petroleum refineries contain one or more carbon monoxide (CO) boilers for waste heat recovery and incineration of off-gases from catalytic cracking operations. These devices constitute a significant fraction of total refinery NO_x emissions. Methods that have been used to reduce NO_x emissions from conventional boilers are either not applicable or have performed poorly when applied to refinery CO boilers. The purpose of the work reported here was to develop and demonstrate in the laboratory NO_x reduction techniques that would be specifically suited to refinery CO boilers.

This project was made possible by funding from EPA and funding provided by the Powerine Oil Company of Santa Fe Springs, CA who also participated in a technical advisory role. Powerine's participation in this project represented an element of an extensive NO_x reduction program undertaken by Powerine over a period of several years to reduce NO_x emissions from a CO boiler at their Santa Fe Springs refinery.

During the course of the program to date, the NO_x reduction approaches being considered as well as the laboratory simulation of the CO boiler have been reviewed with Powerine as well as representatives from other local oil companies. Also during that period, the program was reviewed by the local air pollution control district, industry representatives and the EPA Project Officer.

SECTION 2.0

PROGRAM DESCRIPTION AND OBJECTIVES

The work reported here constituted a portion of a larger overall program, which is shown in Figure 1. The first phase of the program consists mainly of laboratory evaluation of a number of alternative NO_x reduction techniques for refinery CO boilers. Assuming that a technique having sufficient technical merit and cost-effectiveness will result from the laboratory phase, the second phase of the program would consist of field evaluation of that concept on a working refinery CO boiler. As presently envisioned, the second phase would proceed only if a refinery would opt to install the NO_x reduction method at their cost. KVB responsibility in the second phase may include assistance in design and start-up as well as evaluation of the effectiveness and operational impact of the NO_x reduction method. Work performed to date, and reported herein, constitutes Phase I of the program which was sponsored by EPA.

Phase I had the following three major objectives: (1) to simulate in the laboratory a full-scale refinery CO boiler, (2) to investigate the effects of operational variables on NO_x formation in the boiler furnace and, (3) to evaluate combustion modification techniques to reduce the NO_x emissions.

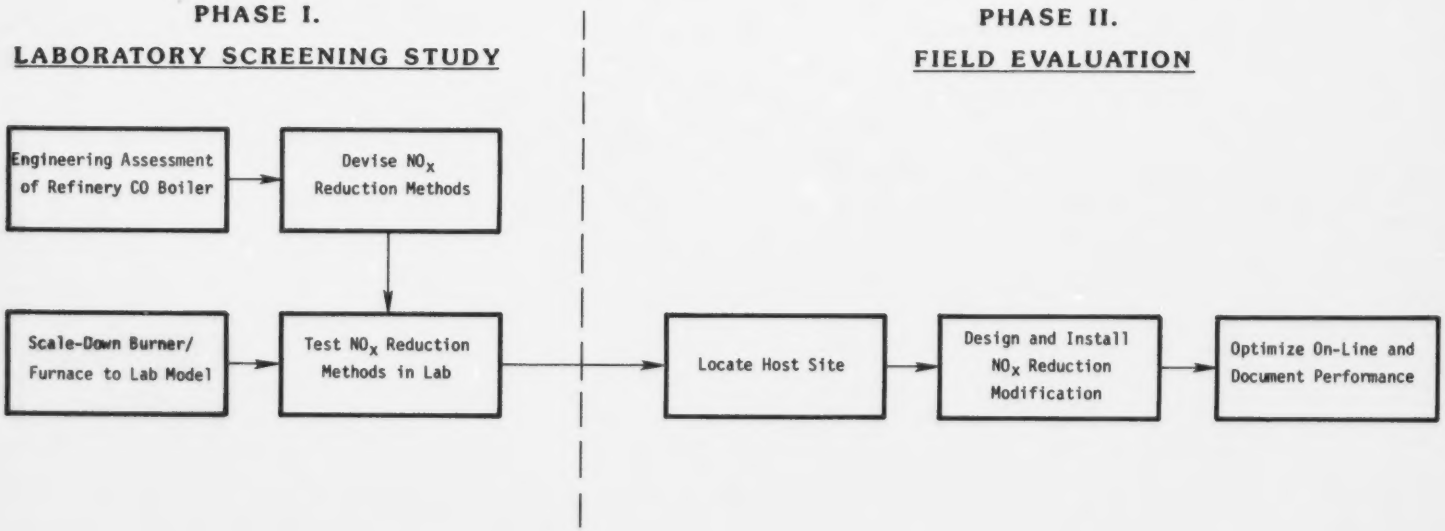
PHASE I.
LABORATORY SCREENING STUDY
PHASE II.
FIELD EVALUATION
Engineering Assessment of Refinery CO Boiler
Devise NO_x Reduction Methods
Scale-Down Burner/ Furnace to Lab Model
Test NO_x Reduction Methods in Lab
Locate Host Site
Design and Install NO_x Reduction Modification
Optimize On-Line and Document Performance

Figure 1. Overall Program Logic

SECTION 3.0

DESCRIPTION OF TYPICAL REFINERY CO BOILER

The primary function of the refinery CO boiler is to incinerate the CO-containing off-gas from the catalytic cracking operation. Virtually all gasoline-producing refineries now use the fluidized catalytic cracking (FCC) process to upgrade the paraffinic contents of gasoline feedstocks. The catalyst employed in this process is subject to "coking," i.e. accumulation of carbonaceous residue on surface of catalyst particles. To remove the coke layer and thus reactivate the surface, the catalyst is circulated through a fluidized combustion unit known as a regenerator. In this unit, the coke layer is burned off the catalyst particles at approximately 975K. For process reasons, slightly sub-stoichiometric quantities of air are admitted to this process, resulting in a regenerator off-gas containing typically a few percent CO. The regenerator off-gas, commonly referred to as CO-gas, is incinerated in the CO boiler. A typical FCC unit/CO boiler arrangement is shown in Figure 2. In most cases, depending upon whether the regenerator includes heat recovery devices, the CO-gas also represents a substantial amount of waste heat (typical flue gas temperatures in the 925-975 K range), the recovery of which is a secondary function of the CO boiler.

The coke deposit on the catalyst particles entering the FCC regenerator invariably contains nitrogen compounds. The presence of this organic nitrogen in an air-deficient combustion atmosphere leads to formation of ammonia and NO_x. With the exception of temporary high-air episodes in the regenerator, the nitrogen is converted primarily to ammonia. Levels of ammonia in the 400 to 1000 ppm range have been observed in the few cases in which measurements have been made. NO_x levels measured on one unit were much lower than this, in the 25 to 100 ppm range. The ammonia and NO_x levels in the CO-gas are undoubtedly influenced by the amounts and types of nitrogen compounds in the refinery feedstock and are possibly influenced further by the regenerator operating condition (temperature and stoichiometry). Recently, an

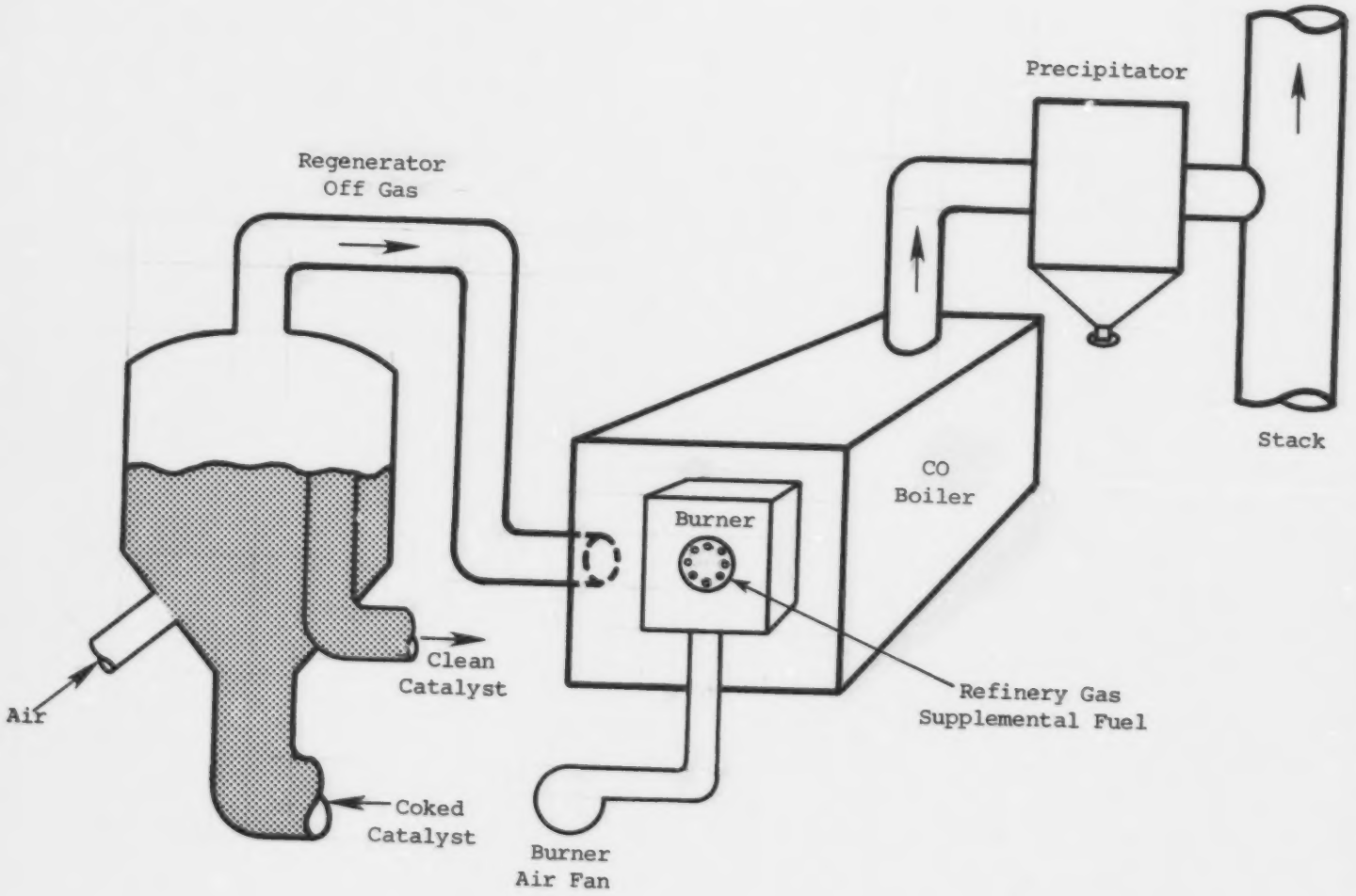

Figure 2. Schematic Drawing of Typical FCC Regenerator with CO Boiler

alternate catalyst has been used in FCC units. The regeneration of this catalyst can be performed at a higher temperature without adversely affecting its reactivity. In this case, the regeneration of the catalyst is performed in an oxidizing atmosphere (excess oxygen) resulting in the production of large quantities of NO_x and low concentrations of ammonia.

In the CO boiler, the CO-gas is incinerated by mixing with a high-excess-air flame from a conventional burner operated typically on refinery gas fuel. The fuel gas burner supplies both heat and oxygen for oxidation of virtually all of the CO to CO_2 provided that the unit is properly designed for rapid and complete mixing of the burner products with the CO-gas. This mixing must occur early in the furnace well before the gases contact convective cooling surface. In most cases, the unit must be designed for effective mixing over a range of fuel/CO-gas input ratios since the boiler may follow refinery steam demand by variation in fuel input rate while CO-gas flow rate remains essentially constant.

NO_x emitted from the CO boiler stems from three sources: (1) oxidation of the ammonia contained in the CO-gas, (2) NO_x entering with the CO-gas, and (3) thermal NO_x produced by the refinery gas flame. Relevant chemical mechanisms for NO_x formation and destruction in the CO boiler furnace are discussed in the next section.

SECTION 4.0

TECHNICAL APPROACH

This section first reviews probable kinetic mechanisms contributing to NO_x formation and destruction in the CO boiler furnace and then considers possible combustion modifications for reducing formation reactions and/or enhancing destruction reactions.

4.1 NO_x FORMATION AND DESTRUCTION MECHANISMS

Two significant NO_x formation mechanisms occur in the CO boiler furnace. The first and most important is oxidation of ammonia (NH_3) entering in the CO-gas (Reaction 1).

$$NH_3 + O_2 \rightarrow NO + H_2O \qquad (1)$$

This oxidation occurs in the presence of excess oxygen at temperatures above approximately 1300K. The second significant mechanism is oxidation of molecular nitrogen entering in air (Reaction 2).

$$N_2 + O_2 \rightarrow 2\ NO \qquad (2)$$

This oxidation occurs at significant rates in the presence of excess oxygen at temperatures above approximately 1800K.

Three competing mechanisms that either destroy NO_x or reduce its formation also can occur in the CO boiler furnace. First, ammonia can alternately be reduced to nitrogen through its reaction with NO at temperatures ranging between approximately 1640 and 1760K. The reaction will proceed only under fuel-rich conditions (Reaction 3).

$$NH_3 + NO \xrightarrow[fuel]{} N_2 + H_2O \quad (3)$$

Second, NO_x already formed can be reduced to nitrogen through its reaction with hydrocarbon species generally present in abundance under fuel-rich conditions (Reaction 4).

$$NO + (HC) \rightarrow N_2 + H_2O \quad (4)$$

Third, ammonia and NO_x can react in the presence of excess oxygen to form nitrogen within the 1200-1300K (approx.) temperature range (Reaction 5).

$$NO + NH_3 \xrightarrow[O_2]{} N_2 + H_2O \quad (5)$$

4.2 NO_x REDUCTION APPROACHES

Control of NO_x formation in conventional gas-fired boilers focuses mainly on a suppression of Reaction (2), via adjustments to reduce simultaneous occurrence of high O_2 and high temperature levels. Common approaches are reduction of burner turbulence, staged air admission and flue gas recirculation. The low-NO_x burner and gas recirculation approaches are inappropriate for CO boiler furnaces in view of the small fraction of total NO_x emanating from Reaction (2) and the need for rapid mixing in order to adequately oxidize the large quantities of CO.

NO_x control in the CO boiler furnace should focus on Reaction 1, the main source of NO_x, or possibly Reaction 5, a unique NO_x destruction path available in this case due to the presence of ammonia. Possible design approaches to reduce NO_x using Reaction 1 or 5 are listed in Table 1. The first two categories, air staging and fuel staging, are based on Reaction 1. The third category, altering the temperature-time history in the furnace, is based on the uniquely temperature-sensitive kinetics of Reaction 5.

Suppression of Reaction (1) appears more likely to result in a reliable NO_x control as opposed to working with the sensitive kinetics of

TABLE 1. NO_x REDUCTION APPROACHES FOR REFINERY CO BOILERS

Air Staging
• NO_x ports around burner
• Air lance on burner centerline
• NO_x ports on furnace sidewalls
• Air register adjustments
Fuel Staging
• Fuel lances around burner
• Low-velocity fuel injection
• Fuel injectors aimed away from burner centerline
• Fuel diverted to CO-gas
• Selected fuel injectors out of service
Temperature-Time
• Optimize location of secondary air injection

Reaction 5. Methods to suppress Reaction (1) will also enhance Reactions (3) and (4), and thus result in the greatest reduction in NO_x emissions.

Two general design approaches are possible. Both attempt to subject the CO-gas to substantial heat in a fuel-rich atmosphere prior to its mixing with excess air. One approach is staged air admission, which was mentioned above. If sufficient combustion air can be directed to a point downstream in the furnace while still burning out CO to acceptably low levels, the front portion of the furnace can be maintained fuel-rich. This would promote destruction of ammonia and NO_x in the CO-gas (Reaction 3 and 4) before oxidation of ammonia (Reaction 1) could occur and would also retard thermal NO_x formation (Reaction 2) at the burner. The most challenging facet of this approach is to achieve sufficiently rapid mixing of the staged air with furnace gases to effect adequate CO oxidation before quenching by convective surface occurs.

Under air staging, as indicated in Table 1, four methods can be considered. The first, use of staged air ports located around the burner, has the advantage of requiring very little furnace modification but may not create a sufficiently fuel rich zone in the front of the furnace. The second, an air lance on the burner centerline, requires more hardware but creates a more distinct staging effect and can direct second stage air exactly where needed to burn out CO in the back portion of the furnace. The third, staged air ports located on the furnace walls, requires significantly more modification work (openings through pressure ports) than center air. However, it has the additional advantage of not requiring hardware to survive in the severe furnace environment. The fourth method, air register adjustments, is by far the easiest to deploy. However, it probably creates the least distinct fuel rich zone and may be operationally difficult.

A second approach to promoting Reactions 3 and 4 is to direct a portion of the fuel supply outward from the burner centerline in an effort to generate a more fuel-rich atmosphere in the CO-gas prior to its mixing with excess air from the burner. As indicated in Table 1, three methods of creating this fuel-rich outer zone can be considered. One is to divert part of the fuel to a set of injectors located around the burner. The second two are to

aim the gas injectors away from the burner centerline or to redesign the injectors for lower injection velocity in order to reduce penetration of fuel toward the burner centerline. The success of the fuel diversion approach depends on the relative rates of the heat transfer, mixing and kinetic processes involved. To the degree that adequate temperature can be generated in the CO-gas prior to its mixing with excess air and that the kinetics of Reactions 3 and 4 are sufficiently rapid, this approach will be effective in reducing NO_x. As indicated in Table 1, this method can be extended from diverting fuel outboard to adding a portion of the fuel directly to the CO-gas upstream of the furnace. The last embodiment of this general approach listed in the table is termination of fuel flow to selected injectors in order to create a fuel-rich zone in a segment within the burner throat.

As indicated in Table 1, optimizing the location of secondary air injection should promote Reaction 5. In this case, controlling the stoichiometry of the primary combustion zone would provide a degree of flexibility in modifying the combustion time-temperature history. Optimizing the location of secondary air injection will insure that oxidizing conditions will occur at the temperature window where Reaction 5 is favored.

SECTION 5.0

DESCRIPTION OF LABORATORY FACILITY AND TEST PROCEDURES

A laboratory-scale CO boiler was assembled at the KVB combustion laboratory in order to test NO_x reduction concepts discussed in Section 4.0.

The sub-scale CO boiler design was based on full-scale unit owned by Powerine Oil Company and operated at their refinery in Santa Fe Springs, CA. This unit (Figure 3) has a single-burner, horizontal furnace with a superheater and side tube passes and a topside economizer. The unit is manufactured by Zurn Industries, Inc.

The sub-scale unit employed an existing water-cooled test furnace rated at 0.88 MW_t to which a scaled-down version of the Powerine boiler front end was retrofitted. The furnace front included a multispud gas burner with concentric CO-gas entry throat (Figure 4) scaled down from the full-scale unit. CO-gas was introduced tangentially to the furnace in a manner similar to the method used in the full-scale unit. Scaling was based on critical entry velocities and furnace residence times. The furnace contained a torus (donut) shaped air plenum which can be located at a variable distance from the burner for supply of second stage combustion air simulating furnace wall NO_x ports (Figure 5). The firing face was equipped with eight NO_x ports arranged around the burner (see Figure 4) and supplied directly from the windbox. The burner could accommodate an air lance for center air staging. The burner gas spuds were adjustable in terms of both immersion depth and orientation of gas orifices. Selected spuds could be relocated to the NO_x ports to achieve the fuel-staging effect discussed in Section 4.0.

The CO-gas supplied to the simulated CO boiler was generated in a second test furnace by the operation of that furnace fuel-rich. The overall equipment arrangement is shown in Figure 6. Control of CO content of the CO-gas was effected by variation of combustion stoichiometry. Control of gas temperature was effected by blending hot gas removed directly from the furnace with cooler gas that had passed through a boiler's firetubes. Ammonia and NO_x

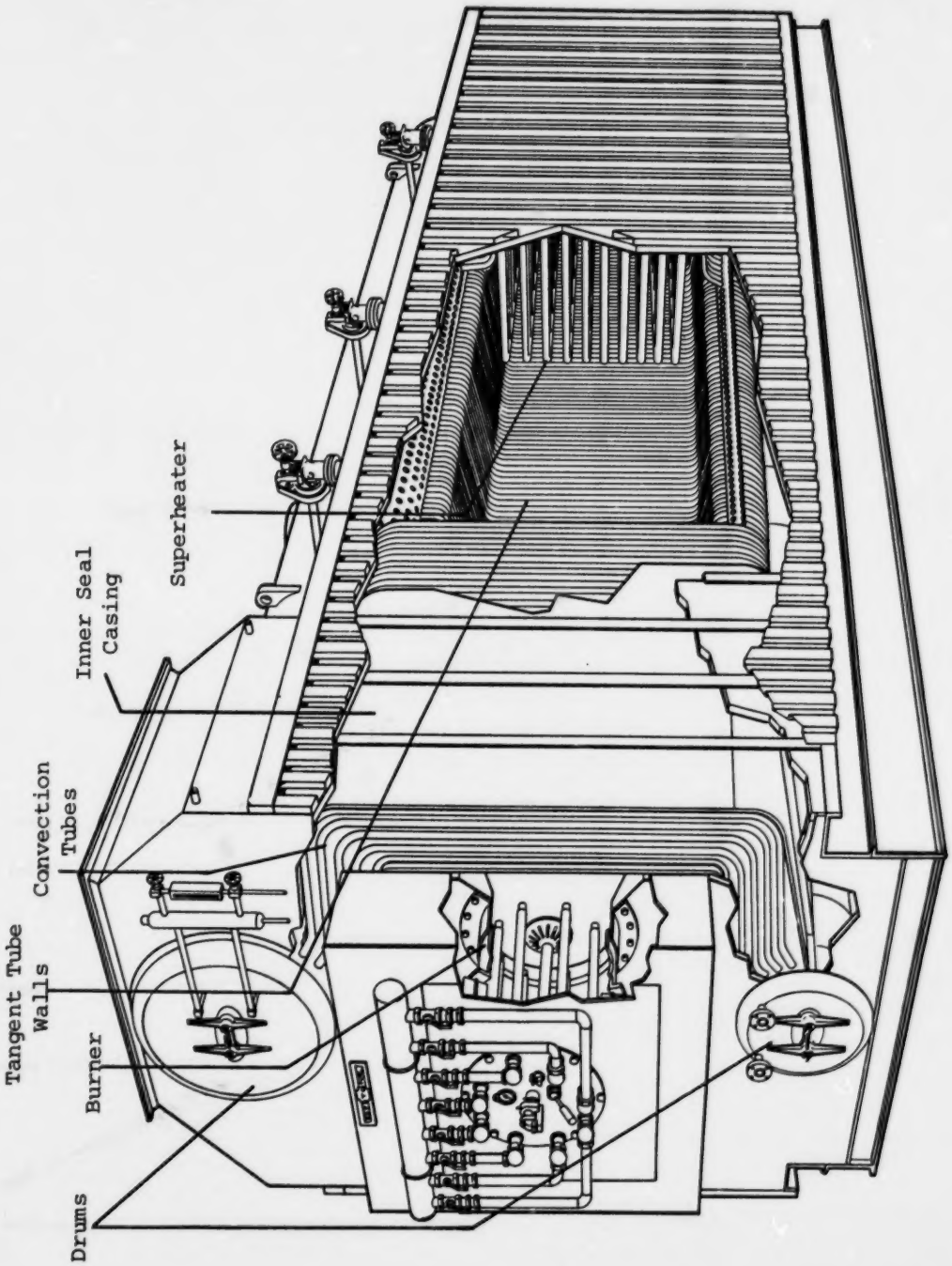

Figure 3. Typical Refinery CO Boiler - Single Burner, Horizontal Furnace Design

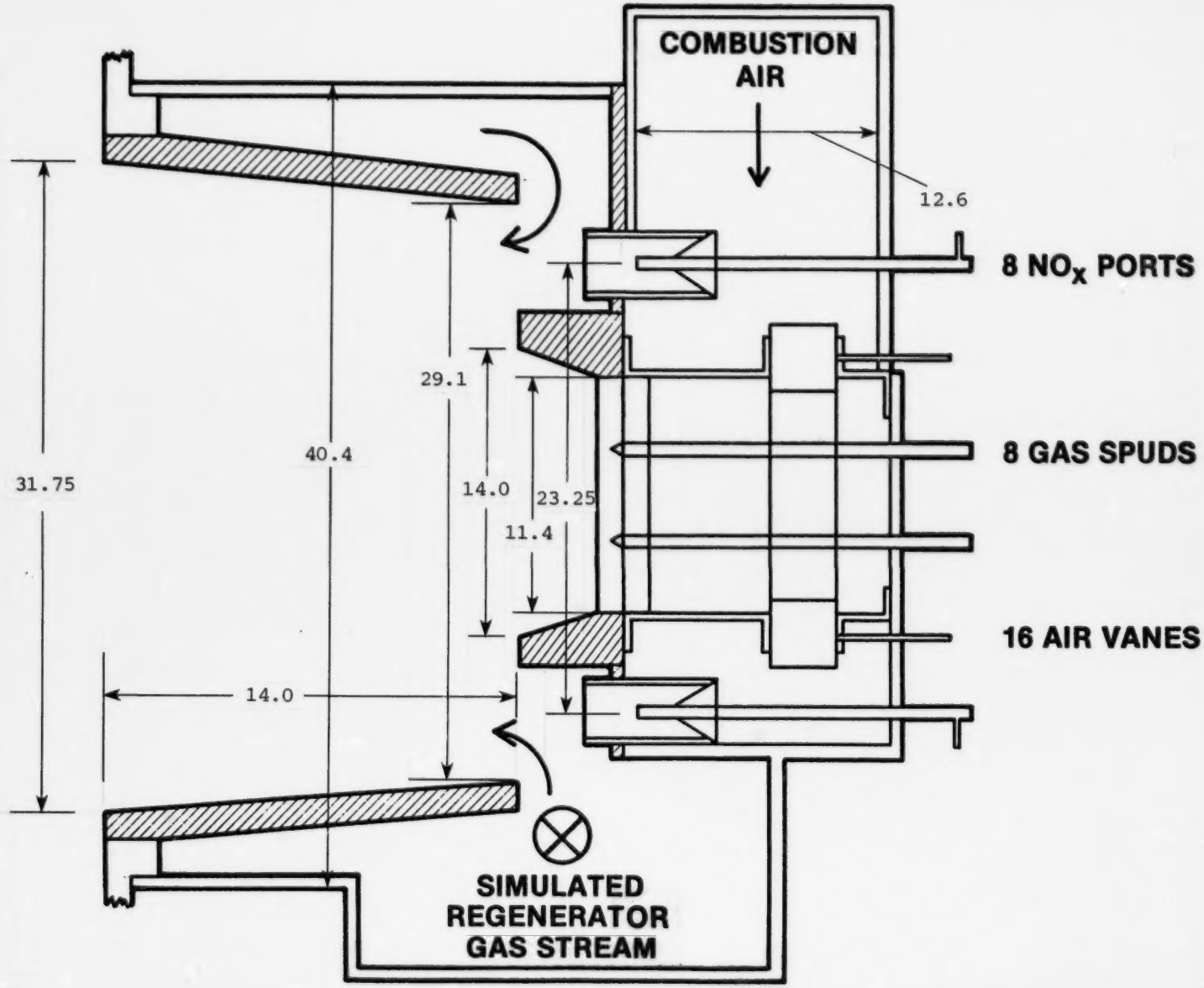

Figure 4. Schematic of Burner and CO-Gas Entry Throat (All dimensions centimeters)

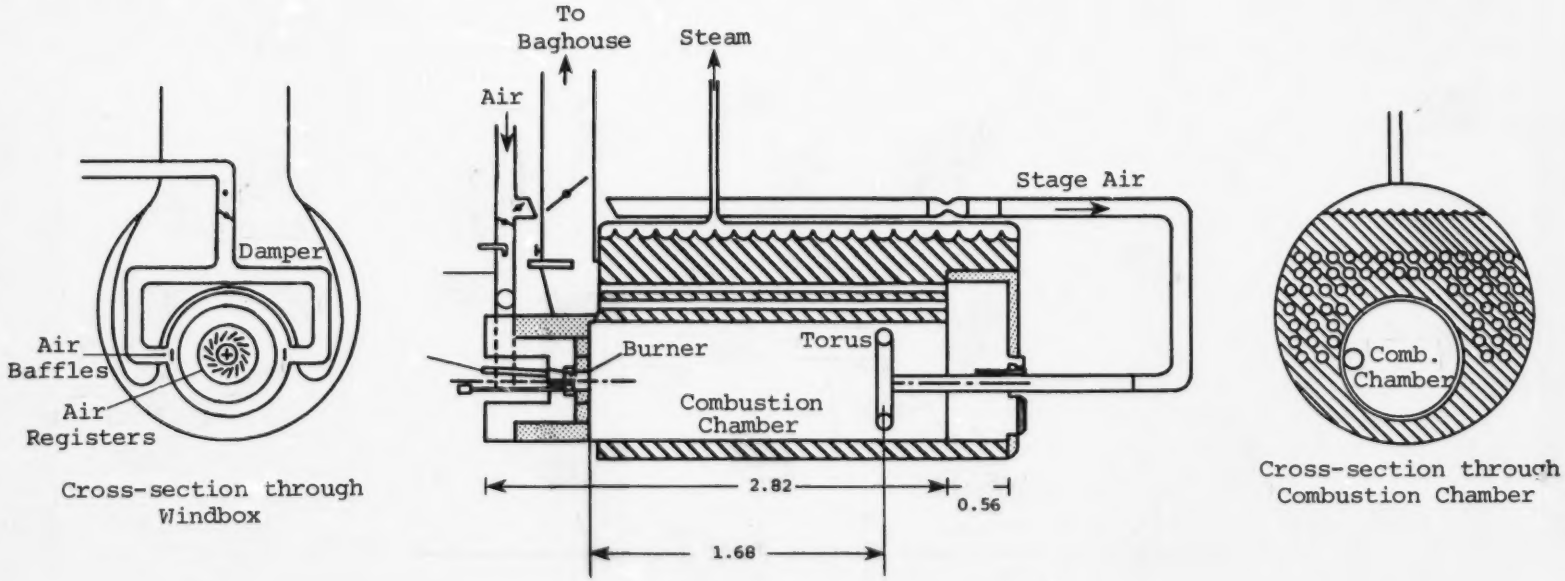

Figure 5. Schematic of the Test Boiler
(dimensions in meters)

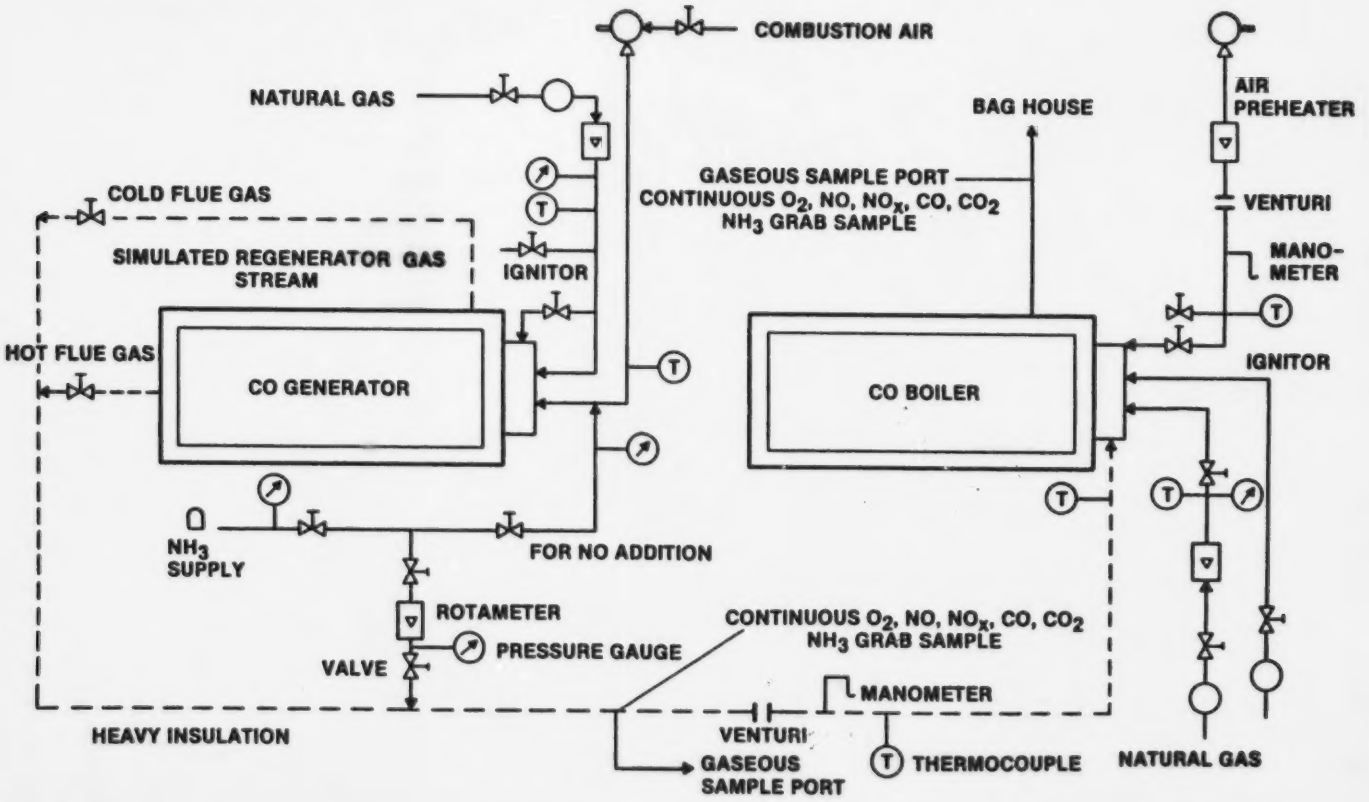

Figure 6. Schematic of Laboratory CO Boiler Simulation System

levels in this gas were controlled by adding ammonia (1) to the fuel burned in the CO-gas generator to produce NO_x and, (2) to the CO-gas to simulate the desired ammonia level. The expected composition of this CO-gas as a function of furnace stoichiometry and gas temperature (without addition of NO_x and NH_3) is shown in Table 2. These expected compositions are based on equilibrium calculations for air/natural gas mixtures.

Flow rates of fuel, air and CO-gas were measured using various metering devices, the equations for which are contained in Appendix A. Critical temperatures were measured using thermocouples. Gas analyses of both CO-gas and CO boiler flue gas utilized the following instrumentation:

NO_x - Thermo Electron Model 10AR, Chemiluminescent
CO - Horiba Model PIR2000, NDIR
O_2 - Teledyne Model 326, Electrolytic
CO_2 - Horiba Model PIR2000, NDIR

All analyzers were zero- and span-checked immediately before or after each test using certified calibration gases.

TABLE 2. CALCULATED CO-GAS COMPOSITION VERSUS CO-GAS GENERATOR STOICHIOMETRY (MOL-FRACTIONS)

	Burner Fuel/Air Ratio, Fraction of Stoichiometric				
	1.1	1.2	1.3	1.4	1.5
Ar		7.90-3			
CH_4		1.26-6			
CO	9.45-3	1.90-2	2.85-2	3.80-2	4.70-2
CO_2		9.10-2			
H		2.80-10			
H_2	2.73-2	5.25-2	7.60-2	9.79-2	1.18-1
H_2O		1.59-1			
NH_3		6.79-6			
N_2		6.70-1			

Notes:

1. Each Mol-Fraction entry should be multiplied by 10 raised to the power indicated (e.g., 9.45-3 = 9.45×10^{-3}).

2. Complete data are shown at 1.2 stoichiometry only. Variations of CO and H_2 versus stoichiometry is included because it entered into data reduction.

SECTION 6.0

RESULTS

The major test variables and results are summarized in Table 3. This table was derived from raw data contained in Appendix B. Fuel and air flow rates were calculated using the flow meter equations contained in Appendix A.

NO_x concentrations are given both on an as-measured and a "net" basis. The net NO_x for any test is the apparent NO_x formation in the CO boiler furnace -- i.e., after deducting NO_x input with the CO-gas. Calculation of net NO_x employs the ratio of CO-gas to total stack gas as follows.

$$NO_x^N = NO_x^S - NO_x^R \cdot R \qquad (1)$$

where

NO_x^N = net NO_x formed in CO boiler furnace, ppm (dry)

NO_x^S = NO_x measurement in stack, ppm (dry)

NO_x^R = NO_x measurement in CO-gas, ppm (dry)

R = Volumetric ratio of CO-gas to total stack gas (dry)

Calculation of the volumetric ratio of CO-gas to stack gas is described in Appendix C.

The values in the last NO_x column in the table (NO_x^{NC}) have been corrected to a constant 120 ppm NO_x level in the CO-gas. This was a relatively minor correction in most cases and makes the data easier to interpret. This correction employed the following equation

$$NO_x^{NC} = NO_x^N + (120 - NO_x^R) * (S - 1) * R \qquad (2)$$

TABLE 3. SUMMARY OF TEST CONDITIONS AND RESULTS*

		CO-GAS GENERATOR						CO BOILER																
		Flow (kg/hr)			Flue Gas Comp.			CO Gas	Flow (kg/hr)				Stoich.		Flue Gas Comp.			Dry	Net	Corr. Net			
Date 1983	Test No.	Fuel	Flue Gas	Air	CO, %	NO_x, ppm	NH_3, ppm	Temp, C	CO	Fuel	Air	Stage Air	Brnr (S1)	Furn (S2)	O_2, %	CO, ppm	NO_x, ppm	Gas Ratio (R)	NO_x, ppm (NO_x^N)	NO_x, ppm (NO_x^{NC})	Inj. OOS	Inj. Pos.	Inj. Ornt.	Comments
						(NO_x^R)	(NH_3^R)																	
3/29	1	62	855	793	2.1	115	0	659	15.2	13.1	485	0	2.15	1.32	2.15	50	124	0.649	53	52	0	7	RI	----------
3/29	2	62	856	794	2.1	117	513	658	15.2	13.1	485	0	2.15	1.32	2.1	50	209	0.649	137	136	0	7	RI	----------
3/29	3	62	856	795	2.1	115	641	657	15.3	13.1	484	0	2.15	1.32	2.1	42	224	0.649	153	152	0	7	RI	----------
3/29	4	59	852	792	1.5	107	624	664	10.8	13.9	484	0	2.01	1.43	2.2	90	177	0.634	112	110	0	7	RI	----------
3/29	5	59	846	787	1.7	112	499	666	12.2	13.9	484	0	2.02	1.38	2.2	100	177	0.637	109	108	0	7	RI	----------
3/29	6	59	847	787	1.5	105	0	665	10.8	13.9	484	0	2.02	1.43	2.2	100	98	0.632	34	32	0	7	RI	----------
3/29	7	63	859	795	3.2	118	0	642	23.2	11.0	483	0	2.56	1.16	2.1	25	122	0.679	46	45	0	7	RI	----------
3/29	8	63	856	793	3.35	109	495	637	24.2	11.0	483	0	2.56	1.13	2.1	28	249	0.682	178	177	0	7	RI	----------
3/29	9	63	845	781	3.6	115	619	628	25.6	10.4	483	0	2.68	1.11	2.1	28	286	0.685	211	210	0	7	RI	----------
3/29	10	66	839	773	4.7	115	619	618	33.1	8.7	483	0	3.22	0.97	2.1	30	325	0.714	247	246	0	7	RI	----------
3/29	11	66	835	770	4.7	110	495	613	33.0	8.5	484	0	3.28	0.98	2.1	40	290	0.713	215	214	0	7	RI	----------
3/29	12	66	836	771	4.75	110	0	612	33.3	8.5	483	0	3.28	0.97	2.1	40	114	0.714	39	38	0	7	RI	----------
4/8	13	62	855	793	2.1	109	0	658	15.2	13.2	575	0	2.53	1.56	3.5	90	122	0.606	54	53	0	7	RI	----------
4/8	14	62	856	794	2.2	113	513	657	16.0	13.2	574	0	2.53	1.52	3.4	80	210	0.609	140	139	0	7	RI	----------
4/8	15	62	857	795	2.2	117	641	655	16.0	13.2	574	0	2.53	1.52	3.4	70	251	0.609	178	178	0	7	RI	----------
4/8	16	59	854	795	1.4	115	641	668	10.2	14.4	574	0	2.31	1.69	3.55	135	196	0.590	126	125	0	7	RI	----------
4/8	17	59	854	795	1.39	115	513	671	10.1	14.3	574	0	2.32	1.70	3.55	135	191	0.590	121	120	0	7	RI	----------
4/8	18	59	853	794	1.4	117	0	672	10.2	14.3	573	0	2.32	1.69	3.55	155	113	0.590	42	41	0	7	RI	----------
4/8	19	63	850	787	3	120	0	649	21.6	11.4	572	0	2.92	1.41	3.5	65	123	0.626	45	45	0	7	RI	----------
4/8	20	63	853	789	3	115	499	643	21.6	11.4	572	0	2.92	1.41	3.5	55	247	0.627	173	172	0	7	RI	----------
4/8	21	63	853	789	3	118	624	642	21.7	11.3	572	0	2.92	1.41	3.55	60	268	0.627	192	191	0	7	RI	----------
4/8	22	66	851	785	3.7	111	624	636	26.7	9.4	572	0	3.52	1.33	3.45	59	313	0.645	240	238	0	7	RI	----------
4/8	23	66	854	787	3.8	115	499	632	27.4	9.4	572	0	3.52	1.31	3.45	40	285	0.648	209	208	0	7	RI	----------
4/8	24	66	855	789	3.85	114	0	629	27.8	9.4	572	0	3.52	1.29	3.45	42	115	0.649	39	38	0	7	RI	----------
4/11	25	62	859	797	2.1	112	0	666	15.3	13.2	462	0	2.02	1.24	1.55	62	112	0.662	43	42	0	7	RI	----------
4/11	26	62	863	801	2.1	112	539	667	15.4	13.2	463	0	2.02	1.24	1.55	55	171	0.663	102	101	0	7	RI	----------
4/11	27	62	863	801	2.1	115	673	667	15.4	13.2	463	0	2.02	1.24	1.5	65	180	0.663	110	109	0	7	RI	----------
4/11	28	59	853	793	1.3	109	632	689	9.4	15.0	462	0	1.79	1.35	1.4	170	121	0.641	57	55	0	7	RI	----------
4/11	29	59	854	794	1.2	115	513	687	8.7	15.0	462	0	1.79	1.38	1.4	265	117	0.639	50	49	0	7	RI	----------
4/11	30	59	854	794	1.3	115	0	686	9.4	15.0	462	0	1.79	1.35	1.4	180	83	0.641	15	14	0	7	RI	----------
4/11	31	64	859	795	3	112	0	668	21.8	11.3	462	0	2.37	1.14	1.5	39	0	0.686	-71	-72	0	7	RI	ABORT
4/11	32	64	863	799	3.1	115	506	660	22.6	11.3	462	0	2.37	1.11	1.5	35	230	0.689	157	156	0	7	RI	----------
4/11	33	64	864	800	3	116	632	655	22.1	11.2	462	0	2.38	1.13	1.45	35	248	0.687	175	174	0	7	RI	----------
4/11	34	67	864	797	3.7	115	631	647	27.0	9.5	462	0	2.81	1.06	1.5	30	295	0.707	220	219	0	7	RI	----------
4/11	35	67	865	798	3.7	119	505	644	27.0	9.5	462	0	2.81	1.06	1.5	30	270	0.707	193	192	0	7	RI	----------
4/11	36	67	865	799	3.7	116	0	643	27.0	9.5	462	0	2.81	1.06	1.5	30	122	0.707	46	46	0	7	RI	----------
4/11	37	62	859	797	2.1	150	545	668	15.3	13.0	510	0	2.27	1.39	2.25	40	235	0.638	143	147	0	7	RI	----------

* See Notes at end

(continued)

TABLE 3. (CONTINUED)*

Date 1983	Test No.	CO-GAS GENERATOR: Flow (kg/hr) Fuel	Flow (kg/hr) Flue Gas	Flow (kg/hr) Air	Flue Gas Comp. CO, %	Flue Gas Comp. NO_x, ppm	Flue Gas Comp. NH_3, ppm	CO Gas Temp, C	CO BOILER: Flow (kg/hr) CO	Flow (kg/hr) Fuel	Flow (kg/hr) Air	Stage Air	Stoich. Brnr (S1)	Stoich. Furn (S2)	Flue Gas Comp. O_2, %	Flue Gas Comp. CO, ppm	Flue Gas Comp. NO_x, ppm	Dry Gas Ratio (R)	Net NO_x, ppm (NO_x^N)	Corr. Net NO_x, ppm (NO_x^{NC})	Inj. OOS	Inj. Pos.	Inj. Ornt.	Comments
						(NO_x^R)	(NH_3^R)																	
4/11	38	76	1036	960	2.4	120	499	633	21.0	13.0	533	0	2.37	1.26	2.25	50	214	0.680	136	136	0	7	RI	----------
4/11	39	62	859	797	2.1	119	499	666	15.3	27.7	760	0	1.59	1.23	2.3	50	171	0.535	110	110	0	7	RI	----------
4/11	40	62	858	796	2.1	115	1298	658	15.3	13.0	510	0	2.27	1.39	2.15	45	272	0.638	202	201	0	7	RI	----------
4/11	41	62	862	800	2.1	48	505	660	15.3	13.0	510	0	2.27	1.39	2.25	45	182	0.639	153	142	0	7	RI	----------
4/14	42	61	855	794	2.2	119	0	653	16.0	13.2	507	0	2.22	1.34	2.0	45	109	0.641	37	37	0	7	RI	NH3 MEASUREMENTS
4/14	43	61	859	798	2.2	111	499	656	16.1	13.2	507	0	2.22	1.34	2.2	40	211	0.642	143	142	0	7	RI	NH3 MEASUREMENTS
4/14	44	61	859	797	2.2	115	624	657	16.0	12.9	507	0	2.27	1.36	2.15	45	232	0.642	162	161	0	7	RI	NH3 MEASUREMENTS
4/15	45	59	851	792	1.4	115	499	680	10.1	14.5	508	0	2.03	1.49	2.25	95	161	0.620	93	91	0	7	RI	NH3 MEASUREMENTS
4/15	46	66	864	799	3.8	111	499	635	27.8	9.8	506	0	3.00	1.13	2.1	35	281	0.685	209	209	0	7	RI	NH3 MEASUREMENTS
4/18	47	60	875	815	2.1	118	513	650	15.6	13.2	510	0	2.24	1.37	2.2	60	209	0.643	136	136	0	7	RI	----------
4/18	48	60	876	816	2.2	119	513	649	16.4	13.2	509	0	2.24	1.34	2.25	70	197	0.645	123	123	0	7	RI	----------
4/18	49	60	868	808	2.2	120	513	647	16.2	13.2	508	0	2.24	1.34	2.2	70	174	0.644	100	100	0	7	RI	SWIRL - 1-16=35
4/18	50	59	868	809	2.3	120	513	644	17.0	13.1	507	0	2.24	1.32	2.25	150	163	0.646	89	89	0	7	RI	SWIRL - LEFT=0, RT.=45
4/18	51	55	874	820	2.1	113	499	643	15.6	13.1	507	0	2.24	1.36	2.2	92	172	0.644	102	101	0	7	RI	SWIRL - 1-3, 12-16=0
4/18	52	55	875	825	2.3	115	499	642	17.1	13.1	507	0	2.25	1.31	2.25	200	168	0.649	96	95	0	7	RI	SWIRL = 7-13=0
4/18	53	55	875	820	2.3	115	499	641	17.1	13.1	507	0	2.25	1.31	2.25	103	171	0.649	99	98	0	7	RI	SWIRL = 1-4, 13-16=0
4/18	54	54	882	828	2.2	118	499	638	16.5	12.9	507	0	2.28	1.34	2.2	50	206	0.648	133	132	1,5-8	7	RI	SWIRL = 1,2, 11-16=0
4/18	55	57	876	819	2.3	112	499	641	17.1	12.9	506	0	2.27	1.32	2.15	575	143	0.649	74	71	1,5-7	7	RI	----------
4/18	56	56	876	820	2.2	112	499	641	16.4	12.9	506	0	2.28	1.35	2.15	200	153	0.647	84	82	1,5,6	7	RI	----------
4/18	57	65	876	857	2.1	118	499	1001	15.6	12.9	506	0	2.28	1.37	2.1	55	189	0.645	117	116	1,5	7	RI	----------
4/18	58	54	876	822	2.1	120	499	640	15.6	12.9	506	0	2.28	1.37	2.2	40	201	0.645	127	127	1	7	RI	----------
4/18	59	56	876	820	2.2	115	499	640	16.4	12.9	506	0	2.28	1.35	2.2	90	163	0.647	92	91	1-4,8	7	RI	----------
4/18	60	57	876	819	2.2	116	499	641	16.4	12.9	506	0	2.28	1.35	2.15	205	134	0.647	62	61	1-4	7	RI	----------
4/18	61	59	876	817	2.3	110	499	641	17.1	12.9	506	0	2.28	1.32	2.2	520	105	0.649	37	33	2-5	7	RI	----------
4/18	62	58	881	823	2.5	112	499	640	18.6	12.9	507	0	2.28	1.27	2.2	250	120	0.655	50	47	2.3.4	7	RI	----------
4/18	63	56	881	825	2.5	120	499	640	18.6	12.9	507	0	2.28	1.27	2.15	95	153	0.655	78	78	2,3	7	RI	----------
4/18	64	55	881	826	2.4	120	499	641	17.9	12.9	507	0	2.28	1.29	2.15	0	183	0.653	108	108	2	7	RI	----------
4/19	65	57	890	833	2.4	115	506	642	18.1	12.9	506	0	2.28	1.29	2.1	82	136	0.656	64	63	1-3	7	RI	----------
4/19	66	59	885	827	2.4	117	506	642	18.0	12.9	506	0	2.28	1.29	2.15	450	104	0.654	31	30	3-5	7	RI	----------
4/19	67	57	885	829	2.3	118	506	642	17.3	12.9	506	0	2.28	1.31	2.15	330	141	0.652	68	67	1-5	7	RI	----------
4/19	68	56	885	829	2.4	118	506	642	18.0	12.9	506	0	2.28	1.29	2.15	80	160	0.654	86	86	1-3,8	7	RI	----------
4/19	69	59	840	826	2.2	78	499	642	16.5	12.9	506	0	2.28	1.34	2.1	510	94	0.650	46	30	3-5	7	RI	----------
4/19	70	59	885	826	2.15	79	499	642	16.1	12.9	506	0	2.28	1.36	2.15	320	104	0.648	55	40	2-4	7	RI	----------
4/19	71	54	885	831	2.3	78	499	642	17.3	12.9	506	0	2.28	1.31	2.15	40	198	0.652	149	142	0	7	RI	----------
4/19	72	54	887	834	2.15	112	513	647	16.2	13.0	508	0	2.27	1.35	2.15	50	208	0.648	139	138	0	7	RI	----------
4/19	73	56	888	832	2.2	119	513	646	16.6	12.9	507	0	2.27	1.34	2.3	130	163	0.649	89	88	0	7	RI	----------
4/19	74	55	889	833	2.3	120	513	644	17.4	12.9	507	0	2.27	1.31	2.25	103	168	0.652	93	93	0	7	RI	PORTS = 1-8
4/19	75	54	884	829	2.2	120	513	644	16.5	12.9	507	0	2.28	1.34	2.2	55	198	0.648	124	124	0	7	RI	PORTS = 1,3,5,7
																								PORTS = 3

* See Notes at end

(continued)

TABLE 3. (CONTINUED)*

Date 1983	Test No.	CO-GAS GENERATOR: Flow (kg/hr) Fuel	Flue Gas	Air	Flue Gas Comp. CO, %	NO_x, ppm (NO_x^R)	NH_3, ppm (NH_3^R)	CO Gas Temp, C	CO BOILER: Flow (kg/hr) CO	Fuel	Air	Stage Air	Stoich. Brnr (S1)	Furn (S2)	Flue Gas Comp. O_2, %	CO, ppm	NO_x, ppm	Dry Gas Ratio (R)	Net NO_x, ppm (NO_x^N)	Corr. Net NO_x, ppm (NO_x^{NC})	Inj. OOS	Inj. Pos.	Inj. Ornt.	Comments
4/19	76	54	888	834	2.1	120	513	644	15.9	12.9	507	0	2.28	1.37	2.2	55	191	0.648	117	117	0	7	RI	PORTS = 3,7
4/19	77	54	888	833	2.15	118	513	645	16.2	12.9	507	0	2.28	1.36	2.3	60	188	0.648	114	114	0	7	RI	PORTS = 2,3
4/19	78	55	888	832	2.1	118	513	646	15.8	12.9	507	0	2.28	1.37	2.3	70	178	0.647	104	104	0	7	RI	PORTS = 2-4
4/19	79	54	888	834	2.1	119	513	646	15.9	12.9	507	0	2.28	1.37	2.2	45	201	0.647	127	127	0	7	RI	PORTS = 7
4/19	80	55	888	833	2.1	112	513	647	15.8	12.9	506	0	2.28	1.37	2.25	75	181	0.648	111	110	0	7	RI	PORTS = 7,8
4/19	81	55	888	833	2.1	115	513	646	15.8	12.9	506	0	2.28	1.37	2.25	90	175	0.648	104	102	0	7	RI	PORTS = 6-8
4/19	82	54	888	834	2.1	115	513	646	15.8	12.9	506	0	2.28	1.37	2.2	60	196	0.648	125	124	0	7	RI	PORTS = 1
4/19	83	55	888	833	2.1	115	513	646	15.8	12.9	506	0	2.28	1.37	2.3	75	182	0.647	110	109	0	7	RI	PORTS = 1,2
4/19	84	55	888	832	2.1	115	513	646	15.8	12.9	506	0	2.27	1.37	2.3	135	171	0.647	99	98	0	7	RI	PORTS = 1,2,8
4/19	85	55	888	832	2.2	118	513	646	16.6	12.9	506	0	2.27	1.34	2.2	100	168	0.650	95	94	0	7	RI	PORTS = 5
4/19	86	56	888	832	2.2	119	513	645	16.6	12.9	506	0	2.28	1.34	2.25	115	158	0.650	84	83	0	7	RI	PORTS = 4,5
4/19	87	56	889	833	2.2	117	513	644	16.6	12.9	506	0	2.28	1.34	2.2	115	158	0.650	85	84	0	7	RI	PORTS = 4-6
4/19	88	56	889	834	2.15	120	513	643	16.2	12.9	506	0	2.27	1.35	2.3	115	162	0.649	87	87	0	7	RI	PORTS = 1-8-1*
4/19	89	55	890	835	2.3	115	513	642	17.4	12.9	506	0	2.28	1.31	2.2	100	168	0.653	96	95	0	7	RI	PORTS = 1,3,5,7-0.5*
4/19	90	55	890	835	2.4	115	506	642	18.1	12.9	506	0	2.28	1.29	2.15	83	177	0.656	105	104	0	7	RI	PORTS = 1,3,5,7-0.25*
4/20	91	54	864	810	2.1	115	513	655	15.4	13.4	511	0	2.22	1.36	2.15	50	224	0.639	154	153	0	5	RI	----------
4/20	92	54	855	801	2.2	120	513	653	16.0	13.3	510	0	2.22	1.34	2.15	50	226	0.639	153	153	0	5	RI	PORTS = 1,3,5,7
4/20	93	54	865	811	2.2	120	513	654	16.2	13.2	509	0	2.24	1.35	2.2	50	220	0.642	146	146	1,5,6	5	RI	----------
4/20	94	54	865	811	2.2	120	506	652	16.2	13.2	509	0	2.24	1.35	2.2	155	196	0.642	122	122	1,5-7	5	RI	----------
4/20	95																				2,5	5	RI	ABORT
4/20	96	57	865	808	2.05	120	506	653	15.1	13.0	509	0	2.28	1.40	2.3	430	143	0.639	69	69	2-5	5	RI	----------
4/20	97	56	865	809	2.2	120	506	654	16.1	13.0	509	0	2.28	1.36	2.25	85	173	0.642	99	99	2,3	5	RI	----------
4/20	98	58	870	857	2.2	115	506	654	16.2	13.0	510	0	2.28	1.36	2.2	270	123	0.643	52	51	2-4	5	RI	----------
4/20	99	57	865	809	2.3	118	506	653	16.9	13.0	510	0	2.28	1.33	2.2	185	158	0.645	85	85	3-5	5	RI	----------
4/20	100	58	865	808	2.2	119	506	653	16.2	12.8	509	0	2.31	1.37	2.3	185	136	0.642	62	62	1-4	5	RI	----------
4/20	101	57	871	814	2.2	118	632	652	16.3	12.8	509	0	2.31	1.36	2.3	190	142	0.644	69	68	1-4	5	RI	----------
4/20	102	54	871	817	2.3	113	499	652	17.0	13.0	509	0	2.28	1.33	2.2	40	211	0.647	141	140	0	5	PP	----------
4/20	103	54	868	815	2.5	119	499	650	18.4	12.9	509	0	2.28	1.28	2.25	35	229	0.650	155	155	0	6	PP	----------
4/20	104	55	868	813	2.4	121	499	649	17.7	12.9	508	0	2.28	1.30	2.1	75	189	0.649	114	114	1,5-8	6	PP	----------
4/20	105	54	867	814	2.4	117	499	650	17.7	12.9	508	0	2.28	1.30	2.2	53	220	0.648	147	147	1,5-7	6	PP	----------
4/20	106	53	868	815	2.4	118	499	649	17.7	12.9	508	0	2.28	1.30	2.1	45	237	0.649	164	164	3-5	6	PP	----------
4/20	107	54	863	810	2.4	116	499	649	17.6	12.9	508	0	2.27	1.31	2.2	40	230	0.647	158	158	1-5	6	PP	----------
4/20	108	57	863	806	2.4	119	499	649	17.6	12.9	508	0	2.28	1.31	2.25	380	144	0.647	70	70	2-6	6	PP	----------
4/20	109	55	863	809	2.4	116	499	649	17.6	12.9	508	0	2.28	1.31	2.2	145	196	0.647	124	123	2-6	6	PP	----------
4/20	110	56	863	807	2.45	117	499	649	17.9	12.9	508	0	2.28	1.29	2.15	165	172	0.648	100	99	4-8	6	PP	----------
4/21	111	63	873	810	2.2	118	510	654	16.3	13.3	509	0	2.21	1.33	7.1	2.E4	43	0.634	-54	-56	0	7	RQ	SWIRL = 1-16=0
4/21	112	59	874	815	2.4	120	499	644	17.8	13.0	510	0	2.27	1.30	2.25	470	98	0.649	23	23	0	7	RQ	SWIRL = 1,5,9,13=35; OTH=15
4/21	113	59	874	815	2.4	115	499	644	17.8	13.0	509	0	2.27	1.30	2.3	370	106	0.649	34	32	0	7	RQ	SWIRL = ALT. 0,45

* See Notes at end

(continued)

TABLE 3. (CONTINUED)*

Date 1983	Test No.	CO-GAS GENERATOR: Flow (kg/hr) Fuel	Flow (kg/hr) Flue Gas	Flow (kg/hr) Air	Flue Gas Comp. CO, %	Flue Gas Comp. NO_x, ppm	Flue Gas Comp. NH_3, ppm	CO Gas Temp, C	CO BOILER: Flow (kg/hr) CO	Flow (kg/hr) Fuel	Flow (kg/hr) Air	Flow (kg/hr) Stage Air	Stoich. Brnr (S1)	Stoich. Furn (S2)	Flue Gas Comp. O_2, %	Flue Gas Comp. CO, ppm	Flue Gas Comp. NO_x, ppm	Dry Gas Ratio (R)	Net NO_x, ppm (NO_x^N)	Corr. Net NO_x, ppm (NO_x^{NC})	Inj. OOS	Inj. Pos.	Inj. Ornt.	Comments
						(NO_x^R)	(NH_3^R)																	
4/21	114	54	868	815	2.2	114	506	642	16.2	13.2	508	0	2.24	1.34	2.2	50	230	0.644	160	159	0	7	RI	LOW VELOC. INJECTORS
4/21	115	60	868	808	2.35	115	506	643	17.3	13.0	508	0	2.27	1.31	2.8	6500	84	0.646	11	8	1,5-8	7	RI	LOW VELOC. INJECTORS
4/21	116	58	868	810	2.3	119	506	643	17.0	13.0	508	0	2.27	1.32	2.3	800	134	0.646	60	60	1,5-7	7	RI	LOW VELOC. INJECTORS
4/21	117	57	863	806	2.4	120	506	643	17.6	13.0	508	0	2.27	1.30	1.3	170	141	0.649	70	70	1,5-6	7	RI	LOW VELOC. INJECTORS
4/21	118	55	859	804	2.5	119	505	642	18.2	13.0	508	0	2.27	1.28	2.2	95	194	0.648	120	120	1,5	7	RI	LOW VELOC. INJECTORS
4/21	119	53	869	816	2.3	122	505	642	17.0	13.0	507	0	2.27	1.32	2.2	45	235	0.647	159	160	1	7	RI	LOW VELOC. INJECTORS
4/22	120	58	881	823	2.3	115	499	639	17.2	13.0	509	0	2.27	1.32	2.35	195	127	0.649	55	53	1-4,8	7	RI	LOW VELOC. INJECTORS
4/21	121	58	881	823	2.3	117	499	639	17.2	13.0	509	0	2.27	1.32	2.25	230	134	0.649	61	60	1-4	7	RI	LOW VELOC. INJECTORS
4/22	122	57	882	825	2.4	119	499	639	18.0	13.0	508	0	2.27	1.29	2.25	155	154	0.652	80	79	2-4	7	RI	LOW VELOC. INJECTORS
4/22	123	60	881	821	2.4	115	499	696	18.0	13.0	508	0	2.27	1.29	2.3	1250	90	0.652	18	16	2-5	7	RI	LOW VELOC. INJECTORS
4/22	124	54	880	871	2.3	115	499	642	17.2	13.0	508	0	2.27	1.32	2.25	60	216	0.649	144	144	2,3	7	RI	LOW VELOC. INJECTORS
4/22	125	54	880	827	2.4	120	499	642	18.0	13.0	508	0	2.27	1.29	2.15	50	220	0.652	145	145	2	7	RI	LOW VELOC. INJECTORS
4/22	126	55	880	825	2.3	119	499	643	17.1	13.0	508	0	2.27	1.32	2.25	55	197	0.649	123	123	1-3	7	RI	LOW VELOC. INJECTORS
4/22	127	59	881	822	2.4	115	499	641	17.9	13.0	508	0	2.27	1.29	2.2	250	114	0.652	42	40	3-5	7	RI	LOW VELOC. INJECTORS
4/22	128	59	882	823	2.3	120	624	639	17.2	12.9	508	0	2.27	1.32	2.25	390	115	0.650	40	40	3-5	7	RI	LOW VELOC. INJECTORS
4/22	129	61	880	820	2.2	123	0	641	16.5	12.9	508	0	2.27	1.35	2.35	600	72	0.647	-5	-3	3-5	7	RI	LOW VELOC. INJECTORS
4/22	130	59	881	822	2.3	119	499	641	17.2	12.9	508	0	2.28	1.32	2.35	240	121	0.649	46	46	1-5	7	RI	LOW VELOC. INJECTORS
4/22	131	56	871	815	2.2	120	499	641	16.3	12.9	508	0	2.28	1.35	2.25	50	173	0.645	99	99	1-3,8	7	RI	LOW VELOC. INJECTORS
4/22	132	57	876	819	2.2	115	499	641	16.4	12.9	507	0	2.28	1.35	2.3	225	146	0.646	74	73	3-5	7	RI	LOW VELOC. INJ. SWIRL = 35
4/22	133	55	878	822	2.3	112	499	638	17.1	12.9	507	0	2.28	1.32	2.2	60	182	0.650	112	111	0	7	PP	LOW VELOC. INJECTORS
4/22	134	57	881	824	2.1	115	499	639	15.7	12.9	507	0	2.28	1.37	2.4	400	145	0.645	73	72	1,5-8	6	PP	LOW VELOC. INJECTORS
4/22	135	55	880	825	2.1	113	499	641	15.7	12.9	507	0	2.28	1.37	2.4	115	187	0.645	116	115	1,5-7	6	PP	LOW VELOC. INJECTORS
4/22	136	55	885	830	2.0	112	499	643	15.1	13.2	507	0	2.22	1.38	2.3	42	190	0.644	121	119	3-5	6	PP	LOW VELOC. INJECTORS
4/22	137	56	885	829	2.1	112	499	643	15.8	13.1	507	0	2.25	1.36	2.4	60	174	0.646	104	102	1-5	6	PP	LOW VELOC. INJECTORS
4/22	138	54	885	831	2.2	118	499	644	16.5	12.9	507	0	2.27	1.34	2.4	65	218	0.648	144	144	2-6	6	PP	LOW VELOC. INJECTORS
4/22	139	58	885	827	2.2	115	499	643	16.5	13.1	507	0	2.24	1.33	2.3	1950	130	0.649	58	57	4-8	6	PP	LOW VELOC. INJECTORS
4/22	140	57	885	829	2.2	115	499	643	16.6	12.9	507	0	2.27	1.34	2.35	90	154	0.649	82	81	1,2,6-8	6	PP	LOW VELOC. INJECTORS
4/22	141	58	885	828	2.1	119	499	643	15.8	13.2	507	0	2.22	1.35	2.3	125	137	0.646	63	63	1-3,7,8	6	PP	LOW VELOC. INJECTORS
4/22	142	57	880	823	2.2	117	499	643	16.5	13.2	506	0	2.21	1.32	2.3	100	143	0.648	70	69	1-4,8	6	PP	LOW VELOC. INJECTORS
4/25	143	62	869	808	2.2	129	506	642	16.2	13.8	507	142	1.53	1.30	2.6	315	61	0.643	-20	-16	0	7	PP	AIR FLOWS NG
4/25	144	59	869	810	2.1	120	506	642	15.5	13.8	507	114	1.65	1.33	2.9	90	112	0.640	36	36	0	7	RI	AIR FLOWS NG
4/27	145	57	882	825	2.4	120	499	636	18.0	13.9	509	61	1.87	1.24	2.65	50	148	0.650	71	71	0	7	RI	----------
4/27	146	60	877	817	2.4	115	499	635	17.9	13.8	509	113	1.66	1.25	2.7	60	98	0.649	25	23	0	7	RI	----------
4/27	147	61	878	816	2.4	120	499	634	17.9	13.8	508	136	1.56	1.25	2.65	180	69	0.650	-7	-7	0	7	RI	----------
4/27	148	56	877	821	2.3	120	499	635	17.1	13.8	508	0	2.13	1.27	1.95	40	161	0.649	87	87	0	7	RI	----------
4/27	149	56	873	816	2.4	120	499	634	17.7	13.2	508	0	2.22	1.28	2.2	45	170	0.650	95	95	0	7	RI	----------
4/27	150	57	873	816	2.35	121	499	634	17.4	13.2	508	0	2.22	1.29	2.25	85	152	0.648	77	77	0	7	RI	PORTS = 1,3,5,7
4/27	151	57	873	816	2.3	120	499	634	17.0	13.2	508	0	2.22	1.31	2.3	115	152	0.647	77	77	0	7	RI	PORTS = 1-8
4/27	152	56	882	826	2.4	120	499	637	18.0	13.1	507	0	2.25	1.28	2.15	55	169	0.653	94	94	0	7	RI	----------

* See Notes at end

(continued)

TABLE 3. (CONTINUED)*

Date 1983	Test No.	CO GAS-GENERATOR: Flow (kg/hr) Fuel	Flow (kg/hr) Flue Gas	Flow (kg/hr) Air	Flue Gas Comp. CO, %	Flue Gas Comp. NO_x, ppm (NO_x^R)	Flue Gas Comp. NH_3, ppm (NH_3^R)	CO Gas Temp, C	CO BOILER: Flow (kg/hr) CO	Flow (kg/hr) Fuel	Flow (kg/hr) Air	Flow (kg/hr) Stage Air	Stoich. Brnr (S1)	Stoich. Furn (S2)	Flue Gas Comp. O_2, %	Flue Gas Comp. CO, ppm	Flue Gas Comp. NO_x, ppm	Dry Gas Ratio (R)	Net NO_x, ppm (NO_x^N)	Corr. Net NO_x, ppm (NO_x^{NC})	Inj. OOS	Inj. Pos.	Inj. Ornt.	Comments
4/27	153	57	882	825	2.4	120	499	637	18.0	13.1	507	43	2.06	1.28	2.3	58	156	0.653	81	81	0	7	RI	AIR LANCE = 2'
4/27	154	57	882	825	2.4	120	499	637	18.0	13.1	507	43	2.06	1.28	2.3	55	155	0.653	80	80	0	7	RI	AIR LANCE = 3'
4/27	155	56	882	826	2.4	120	499	637	18.0	13.1	507	43	2.06	1.28	2.2	55	163	0.653	88	88	0	7	RI	AIR LANCE = 4'
5/2	156	56	841	786	2.2	120	499	645	15.7	13.3	509	0	2.21	1.35	2.1	75	189	0.636	116	116	0	7	RI	INJECTORS 1,3,5,7 TO PORTS
5/2	157	56	842	786	2.4	115	499	644	17.1	13.3	508	0	2.21	1.30	2.15	85	181	0.641	111	110	0	7	RI	----------
5/2	158	55	836	781	2.4	115	499	646	17.1	13.3	508	0	2.21	1.30	2.15	55	200	0.639	130	129	0	7	RI	FUEL TO CO GAS: 25%
5/2	159	54	835	781	2.3	119	499	647	16.3	13.3	508	0	2.22	1.33	2.1	55	214	0.637	142	142	0	7	RI	FUEL TO CO GAS: 50%
5/2	160	54	836	781	2.4	119	499	644	17.1	13.3	508	0	2.22	1.30	2.1	55	214	0.639	142	141	0	7	RI	FUEL TO CO GAS: 75%
5/2	161	55	838	784	2.4	125	499	641	17.1	13.3	508	0	2.22	1.30	2.2	55	211	0.640	134	135	0	7	RI	FUEL TO CO GAS:100%
5/2	162	58	835	777	2.3	115	499	646	16.3	13.2	507	43	2.03	1.33	2.6	400	148	0.636	76	75	0	7	RI	AIR LANCE = 2' (NG)
5/2	163	57	835	778	2.3	115	499	646	16.3	13.2	507	43	2.03	1.33	2.4	200	163	0.637	92	91	0	7	RI	AIR LANCE = 3' (NG)
5/2	164	55	835	780	2.3	115	499	646	16.3	13.2	507	43	2.03	1.33	2.5	65	204	0.636	133	132	0	7	RI	AIR LANCE = 0' (NG)
5/2	165	60	836	776	2.4	115	499	643	17.0	13.2	507	105	1.76	1.30	0.7	125	97	0.643	31	30	0	7	RI	AIR LANCE =14.5"(NG)
5/2	166	59	836	777	2.3	115	456	642	16.3	13.2	507	86	1.84	1.33	1.05	175	104	0.640	38	36	0	7	RI	AIR LANCE =14.5"(NG)
5/3	167	60	834	775	2.4	125	499	637	17.0	13.1	508	105	1.78	1.31	3.1	400	101	0.637	21	23	2-4	7	RI	----------
5/3	168	59	836	776	2.3	135	456	635	16.3	13.3	507	105	1.75	1.33	2.0	150	107	0.638	25	31	0	7	RI	----------
5/3	169	56	834	778	2.4	105	499	637	17.0	13.2	506	61	1.95	1.30	2.3	60	181	0.639	116	113	0	7	RI	----------
5/3	170	60	838	778	2.3	112	492	631	16.4	13.2	403	78	1.42	1.16	2.25	500	102	0.670	30	27	0	7	RI	AIR LANCE = 15.5"
5/3	171	60	838	778	2.3	112	492	631	16.4	13.2	403	78	1.42	1.16	2.2	440	96	0.670	24	21	0	7	RI	AIR LANCE = 21.5"
5/3	172	61	838	777	2.3	112	492	631	16.4	13.2	403	78	1.42	1.16	2.2	825	84	0.670	12	9	0	7	RI	AIR LANCE = 27.5"
5/3	173	59	833	775	2.1	125	492	629	14.9	13.0	457	44	1.83	1.27	2.5	300	131	0.653	52	53	0	7	RI	AIR LANCE = 21.5"
5/3	174	59	833	775	2.1	125	492	629	14.9	13.0	457	44	1.83	1.27	2.4	300	126	0.653	47	49	0	7	RI	AIR LANCE = 27.5"
5/3	175	58	833	776	2.1	125	492	629	14.9	13.0	457	44	1.83	1.27	2.45	320	141	0.653	62	63	0	7	RI	AIR LANCE = 15.5"
5/3	176	58	833	776	2.3	120	492	629	16.3	13.0	481	18	2.06	1.22	2.3	290	149	0.659	73	73	0	7	RI	AIR LANCE = 15.5"
5/3	177	58	833	776	2.3	120	492	629	16.3	13.0	481	18	2.06	1.22	2.35	380	145	0.659	69	69	0	7	RI	AIR LANCE = 21.5"
5/3	178	57	833	776	2.3	120	492	629	16.3	13.0	481	18	2.06	1.22	2.25	160	154	0.659	78	78	0	7	RI	AIR LANCE = 27.5"
5/5	179	57	836	779	2.2	119	499	633	15.6	13.2	509	0	2.23	1.36	2.0	120	143	0.634	71	71	2-4	M	RI	LONG DIVERGNT THROAT
5/5	180	57	838	781	2.3	125	499	628	16.4	13.2	509	0	2.23	1.33	2.0	100	157	0.637	81	83	2-4	7	RI	LONG DIVERGNT THROAT
5/5	181	54	838	784	2.4	125	499	628	17.1	13.2	509	0	2.23	1.31	1.9	55	207	0.640	132	132	0	7	RI	LONG DIVERGNT THROAT
5/6	182	57	844	788	2.3	115	499	627	16.5	13.1	508	0	2.24	1.33	2.3	230	164	0.639	93	92	2-4	7	RI	LONG STRAIGHT THROAT
5/6	183	56	840	784	2.4	115	499	625	17.1	13.1	508	0	2.24	1.31	2.25	80	190	0.640	119	118	2-4	M	RI	LONG STRAIGHT THROAT
5/6	184	54	841	786	2.3	115	499	624	16.4	13.1	507	0	2.24	1.33	2.2	50	225	0.639	155	154	0	7	RI	LONG STRAIGHT THROAT
5/10	185	56	859	803	2.3	128	499	621	16.8	13.6	507	0	2.16	1.29	2.35	60	198	0.643	119	120	0	7	RI	----------
5/10	186	59	860	801	2.4	117	499	618	17.6	13.8	507	0	2.13	1.26	2.35	400	124	0.646	51	50	3-5	7	RI	----------
5/10	187	59	862	803	2.4	102	1295	616	17.6	13.7	507	0	2.13	1.26	2.35	630	130	0.647	66	59	3-5	7	RI	----------
5/10	188	59	860	802	2.4	60	1282	617	17.6	13.7	507	0	2.13	1.26	2.35	550	130	0.646	93	69	3-5	7	RI	----------
5/10	189	60	862	802	2.4	55	499	615	17.6	13.7	506	0	2.13	1.26	2.4	600	106	0.647	72	46	3-5	7	RI	----------
5/10	190	64	861	797	2.3	60	0	616	16.8	13.7	506	0	2.13	1.28	2.4	2250	39	0.644	2	-22	3-5	7	RI	----------

(continued)

* See Notes at end

TABLE 3. (CONTINUED)*

		CO GAS-GENERATOR						CO BOILER															
		Flow (kg/hr)			Flue Gas Comp.				Flow (kg/hr)				Stoich.		Flue Gas Comp.								
Date 1983	Test No.	Fuel	Flue Gas	Air	CO, %	NO_x, ppm	NH_3, ppm	CO Gas Temp, C	CO	Fuel	Air	Stage Air	Brnr	Furn	O_2, %	CO, ppm	NO_x, ppm	Dry Gas Ratio	Net NO_x, ppm	Corr. Net NO_x, ppm	Inj. OOS	Inj. Pos.	Inj. Ornt.	Comments
						(NO_x^R)	(NH_3^R)						(S1)	(S2)				(R)	(NO_x^N)	(NO_x^{NC})				
5/10	191	54	845	790	1.15	110	499	647	8.3	15.5	506	0	1.90	1.49	2.4	70	164	0.613	99	97	0	7	RI	----------
5/10	192	58	845	788	1.2	116	499	645	8.6	15.5	506	0	1.90	1.47	2.5	930	100	0.614	31	29	3-5	7	RI	----------
5/10	193	58	846	788	1.1	109	1295	644	7.9	15.5	506	0	1.90	1.50	2.5	1800	96	0.612	31	27	3-5	7	RI	----------
5/10	194	58	846	788	1.2	61	1282	643	8.7	15.5	506	0	1.90	1.47	2.45	1890	92	0.614	56	34	3-5	7	RI	----------
5/10	195	59	846	788	1.0	65	499	642	7.2	15.5	505	0	1.89	1.53	2.5	1800	87	0.610	48	28	3-5	7	RI	----------
5/10	196	62	846	784	1.0	62	0	644	7.2	15.4	505	0	1.90	1.53	2.7	4000	30	0.610	-7	-29	3-5	7	RI	----------
5/10	197	56	856	800	2.1	115	499	624	15.3	19.8	609	0	1.79	1.26	2.2	40	170	0.592	105	104	0	7	RI	----------
5/10	198	59	850	791	2.1	115	499	626	15.1	20.0	609	0	1.77	1.26	2.25	125	130	0.590	65	63	3-5	7	RI	----------
5/10	199	57	850	793	2.2	125	1282	626	15.9	19.9	609	0	1.77	1.24	2.2	120	162	0.592	91	93	3-5	7	RI	----------
5/10	200	57	860	804	3.5	120	499	616	25.4	11.3	505	0	2.59	1.13	2.2	55	249	0.676	171	171	0	7	RI	----------
5/10	201	59	862	803	3.5	120	499	614	25.5	11.3	505	0	2.59	1.13	2.2	80	191	0.676	113	113	3-5	7	RI	----------
5/10	202	56	863	807	3.5	120	1295	612	25.5	11.3	505	0	2.59	1.13	2.25	90	258	0.676	180	180	3-5	7	RI	----------
5/10	203	57	864	807	3.6	59	1282	610	26.3	11.3	505	0	2.59	1.11	2.2	85	239	0.679	201	176	3-5	7	RI	----------
5/10	204	60	863	803	3.45	58	499	611	25.2	11.3	506	0	2.59	1.14	2.35	110	169	0.675	131	106	3-5	7	RI	----------
5/10	205	67	863	795	3.6	58	0	612	26.3	11.3	506	0	2.59	1.11	2.35	220	48	0.678	10	-15	3-5	7	RI	----------

Notes:

1. Flue gas compositions are dry basis.

2. NO_x concentrations in CO boiler flue gas are corrected to 3% O_2.

3. Burner stoichiometry (S1) = $\frac{\text{air entering via burner}}{\text{air required to burn fuel entering via burner}}$

   Furnace stoichiometry (S2) = $\frac{\text{air entering via burner}}{\text{air required to burn all fuel, CO and } H_2 \text{ entering furnace}}$

4. Dry Gas Ratio (R) = CO Gas/Total Stack Gas (dry basis, volumetric)

5. "Net NO_x" (NO_x^N) = net NO_x formed in CO boiler after deduction of NO_x in regenerator gas.

6. "Corrected Net NO_x" (NO_x^{NC}) is corrected to 120 ppm NO_x in regenerator gas.

7. Injectors OOS = out of service (fuel flow stopped)

8. Injector Positions:
   7 = Nominal
   5,6 = Deeper insertion
   M = Maximum insertion

9. Injector Orientation Patterns:
   RI = Radially inward
   RO = Radially outward
   PP = Powerine pattern (unsymmetrical, as found)

10. In Comments:
    "Ports" indicates NO_x ports open around burner
    "Swirl" indicates register vane angle (0 = radial)

where

NO_x^{NC} = net NO_x formed in CO boiler furnace, corrected to 120 ppm CO-gas NO_x level.

S = approximate survival rate of NO_x^R in passing through the CO boiler.

This correction is described in more detail in Appendix D.

In scanning the data in Table 3, operating ranges and results on the laboratory boiler in nominal operation can be compared to those found on the full-scale boiler at the Powerine refinery. This comparison (Table 4) shows the laboratory model to comprise a good facsimile of the full-scale boiler in terms of ranges of key operating parameters and NO_x levels produced. The ranges of data shown for the full-scale boiler were based on engineering and source tests conducted by local and state air quality control agencies and KVB during 1980-1982.

In the first segment of testing, Tests 1 through 47, operational variables were examined. Key operating variables included NO_x, ammonia and CO concentrations in the CO-gas, the ratio of CO-gas to stack gas, and burner stoichiometry. The bulk of the testing, Tests 48 through 184, focused on the various NO_x reduction methods described in Section 4. During these tests each method was tested separately and, where justified, in combination with one or more other methods. For most methods tested, a series of tests was required in order to optimize the method and, if successful, to test the effects of operational variables on the effectiveness of the method. During this segment of testing, operating variables were basically held over a constant range of values:

CO-Gas Composition	
CO	2.1-2.5%
NH_3	490-515 ppm
NO_x	110-120 ppm
Ratio of CO-gas to stack gas	~0.65
CO boiler burner stoichiometry	~2.25

TABLE 4. COMPARISON OF OPERATING RANGES AND NO_x LEVELS PRODUCED -- LABORATORY BOILER VERSUS FULL-SCALE BOILER

	Normal Operation With CO-Gas		Boiler Only - No CO-Gas	
	Full-Scale	Laboratory**	Full-Scale	Laboratory
CO-Gas (dry):				
CO, %	1.8-3.4	1.2-4.8	-	-
NO_x, ppm	45-120	48-150	-	-
NH_3, ppm	470-620	490-675	-	-
Temp., K	~975	~935	-	-
Fuel to Burner, MW_t	~20.5	~0.2		
Stack Gas (dry):				
O_2, %	1.0-3.5	1.4-3.6	3.4-3.6	3.5
CO, ppm	50-700	30-265	120-600	30-40
NO_x, ppm*	105-270	117-325	40-51	40-60
Dry Volumetric Ratio of CO-gas to Stack Gas	0.52-0.62	0.54-0.71	-	-

*Corrected to 3% O_2

**Tests 1-47

In the last phase of testing, Tests 185-208, operational variables were again varied in conjunction with one operational technique for NO_x reduction -- that of stopping fuel to selected injectors.

In the following presentation of results, the effects of operational variables on NO_x formation in the CO boiler will be discussed first. This will be followed by the results of the various NO_x control methods in the order of: (1) minor burner modifications, (2) staging the combustion, and (3) major burner modifications.

6.1 EFFECTS OF OPERATING VARIABLES

The most significant operating variables affecting NO_x formation in the CO boiler furnace are the ammonia content of the CO-gas (NH_3^R) and the stoichiometry (fraction of stoichiometric air) at which the burner operates. Figure 7 shows the effects of these two variables with other operating variables being held virtually constant. The data were correlated to both burner and furnace stoichiometry, S1 and S2 respectively, which were defined as follows:

$$S1 = \frac{\text{air to burner}}{\text{air required to burn fuel entering via burner}}$$

$$S2 = \frac{\text{air to burner}}{\text{air required to burn all fuel, CO and } H_2 \text{ entering furnace}}$$

The data correlate best with burner stoichiometry (S1) and do not correlate as well with furnace stoichiometry (S2). The NO_x emissions did not correlate with furnace stoichiometry since the combustion air and CO-gas did not instantly mix. The CO-gas was introduced along the furnace wall while combustion air was injected into the center of the furnace. Having more or less fuel (CO + H_2) in the CO-gas did not therefore directly influence the overall combustion stoichiomietry in the flame basket. Burner stoichiometry, on the other hand, dictated the level of oxygen available to react with CO-gas producing NO_x by the oxidation of the ammonia. High burner stoichiometry

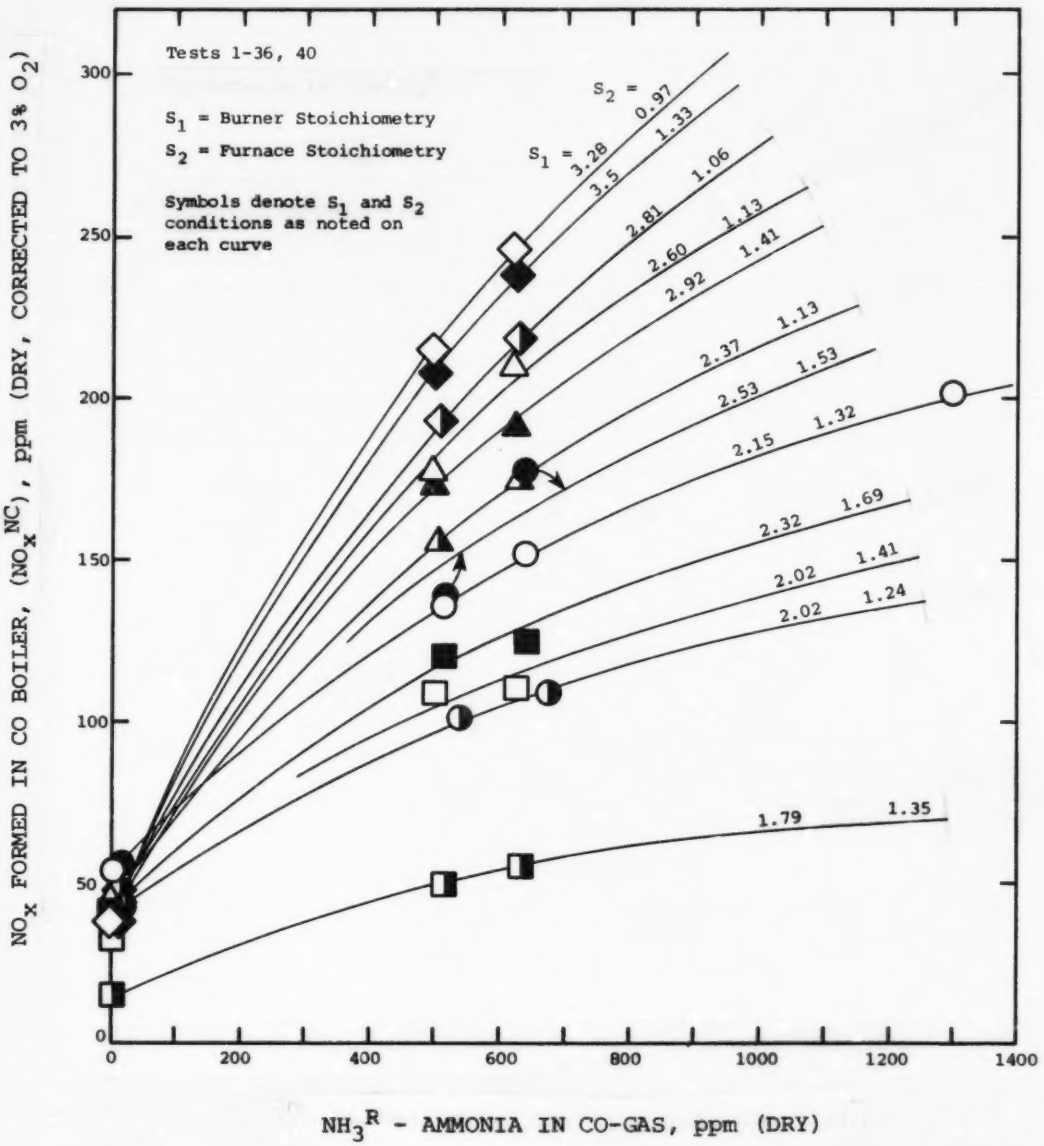

Figure 7. Effect of ammonia content of CO-gas and burner stoichiometry on NO_x formation in CO boiler.

provided larger quantities of oxygen to more efficiently convert the ammonia to NO_x. Conversely, low burner stoichiometry minimized the amount of oxygen available and thus inhibited the ammonia conversion to NO_x.

Figure 8 shows the aggregate* and marginal† conversion rates of NH_3^R to NO_x versus burner stoichiometry at approximately 500 ppm NH_3^R. The data plotted in this fashion clearly show the strong effect of burner stoichiometry on ammonia conversion rate, which varies from 10 to 55 percent depending on the stoichiometry. This plot also shows that the conversion rate approached zero at a burner stoichiometry of approximately 1.5 or less.

Figure 9 shows the effect of NO_x concentration in the CO-gas on NO_x in the stack - i.e., the NO_x survival rate as it passes through the furnace. Under typical unstaged combustion conditions, approximately 75 percent of the NO_x in the CO-gas appears in the stack (slope of the curve in Figure 9 divided by R, the dry volumetric ratio of CO-gas to stack gas). When combustion is staged, in this case by stopping fuel flow to selected injectors, the survival rate of regenerator NO_x is decreased as would be expected. Also as expected, the data indicate that the survival rate has a strong dependence on burner stoichiometry.

Figure 10 summarizes the effect of burner stoichiometry on NO_x formation in the furnace under two conditions - with approximately 500 ppm ammonia in the CO-gas (upper curve) and with no ammonia in the CO-gas (lower curve). The upper curve once again illustrates the strong effect of burner stoichiometry on ammonia conversion to NO_x in the furnace. The lower curve indicates that thermal NO_x formation is enhanced by the introduction of the CO-gas. Generally, the boiler burner will produce a NO_x level in the range of 13-20 ppm (40-60 ppm measured with regenerator off [see Table 4] diluted by a dry gas volume ratio of approximately 3:1). The fact that thermal NO_x levels much higher than this are produced when CO-gas was introduced indicates that the

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*Aggregate conversion rate is the fraction of total NH_3^R appearing on NO_x in the stack.

†Marginal conversion rate is the fraction of a small increase in NH_3^R that appears as an increase in NO_x in the stack.

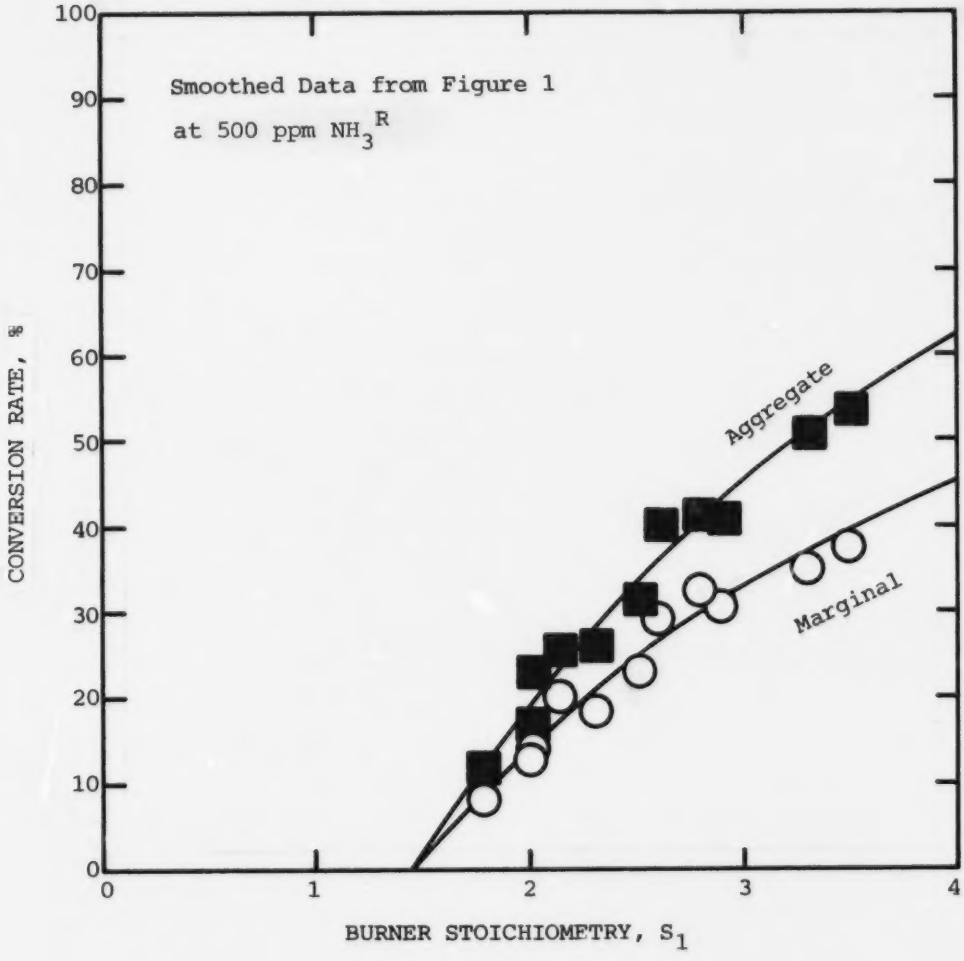


Figure 8. Effect of Burner Stoichiometry on Conversion of Ammonia to NO_x

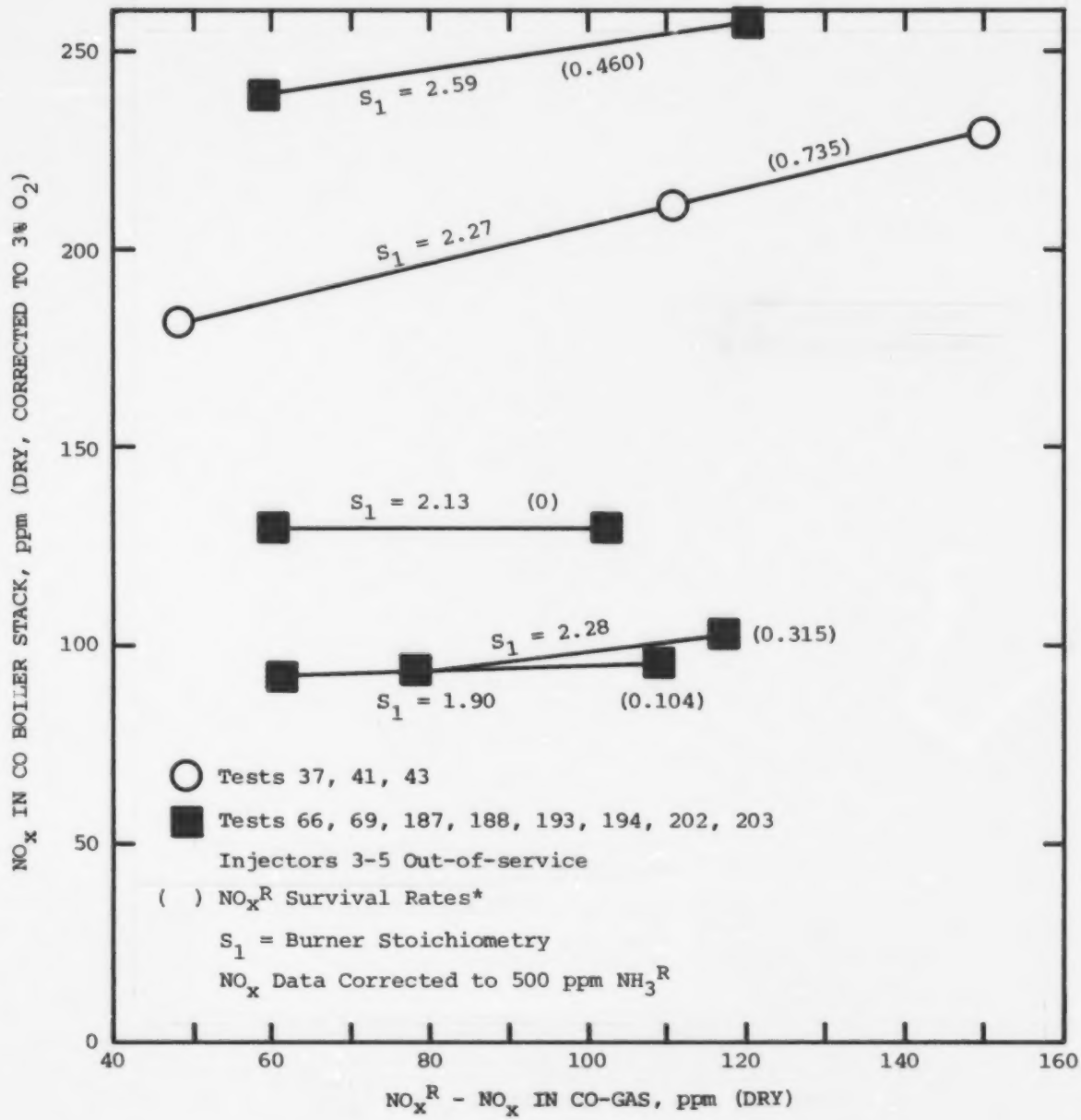


Figure 9. Effect of NO_x in CO-gas on NO_x in Stack

*Fraction of NO_x passed through the boiler furnace unaltered.

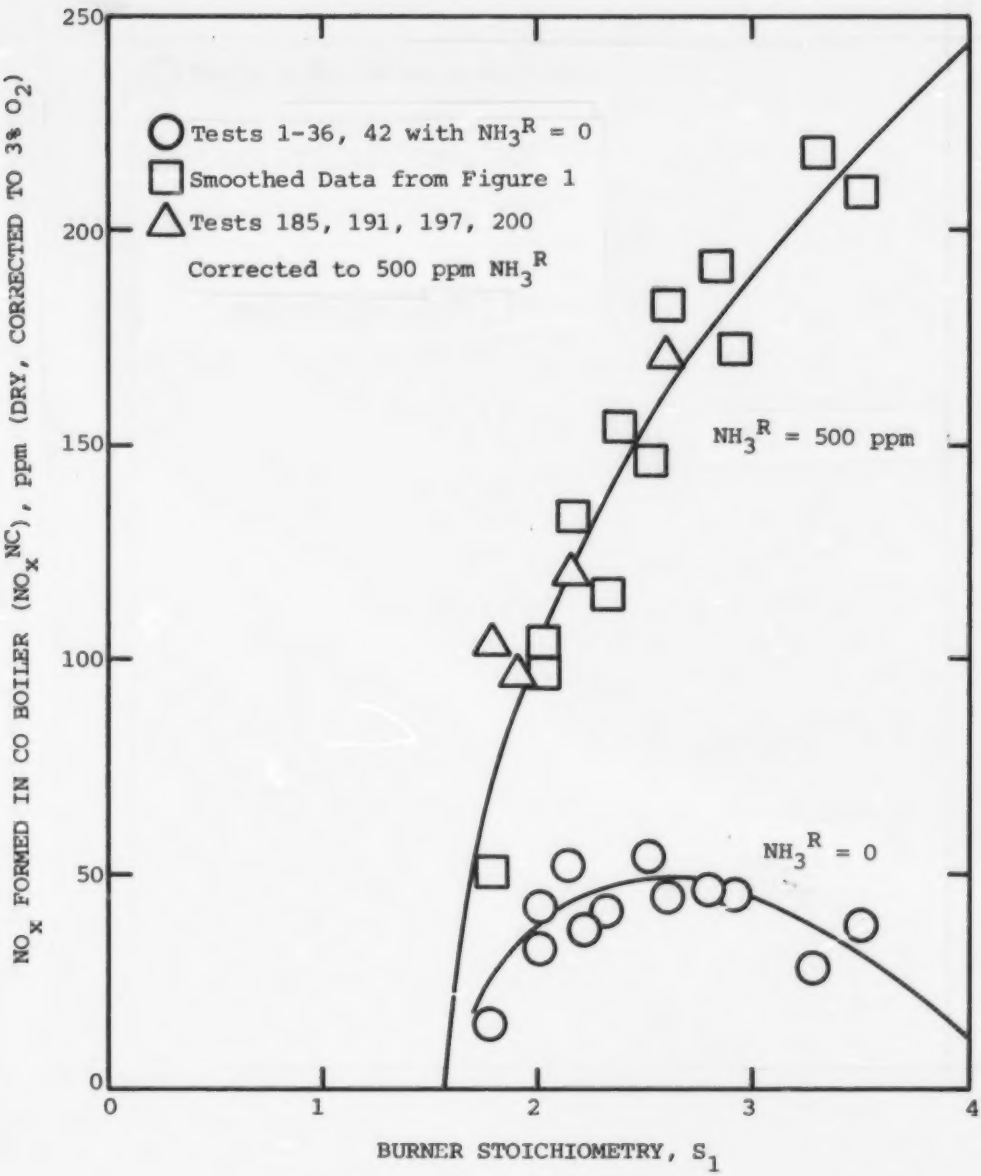


Figure 10. Effect of Burner Stoichiometry on NO_x Formation in CO Boiler

CO-gas plays some role in thermal NO_x formation either by raising the temperature of the burner flame zone or by producing sufficiently high temperatures in CO and H_2 combustion for NO_x formation to occur. In viewing the lower curve, it is also noted that net thermal NO_x formation declines as burner stoichiometry is either increased or decreased from approximately 2.6. The decline in thermal NO_x^N with decreasing stoichiometry probably reflects the reduced survival of regenerator NO_x at lower stoichiometries that was noted above in Figure 9 -- i.e., not an actual reduction in thermal NO_x which would not be expected at these still relatively high levels of burner air fuel ratio. Reduction in thermal NO_x^N with increasing stoichiometry probably represents an actual decline in thermal NO_x resulting from cooling of the flame zone at excessively high levels of excess air.

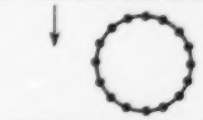
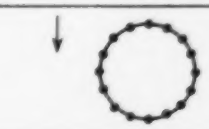
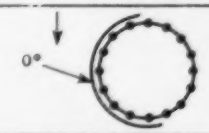
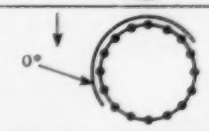
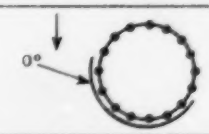
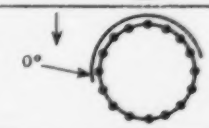
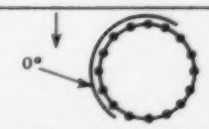
An attempt was made to correlate the offset of individual data points from the upper curve in Figure 10 with furnace stoichiometry S2, stack O_2 level and CO level in the CO-gas. None of these variables successfully correlated the offsets and thus no secondary parameters were defined. It was noted that the stack O_2 level did not correlate well with overall air and fuel flows to the system. This may indicate that a problem was occurring with the stack O_2 measurement system.

6.2 MINOR BURNER MODIFICATIONS

Minor burner modifications that were tested for their effects on NO_x included air register adjustment, gas injector positioning and orientation and fuel injector redesign for lower velocity injection.

The burner air register consisted of 16 vanes on a circle pattern around the throat inlet. These vanes could be adjusted individually from 0° (wide open) to 90° (closed). Their normal position was 45°. The results of air register adjustments are shown in Table 5. In the first series of tests air vanes were opened simultaneously to reduce air swirl. This produced a minor NO_x reduction but was limited by flame instability, as indicated in the table. In a second series of tests, vanes were fully opened on selected segments of the register in order to bias the air and produce some staging of the combustion. This method produced significant NO_x reductions to as low as

TABLE 5. EFFECT OF AIR REGISTER ADJUSTMENTS ON NO_x FORMATION

Test No.	Air Register Pattern**	NO_x^{NC}, ppm (dry, corrected to 3% O_2)*
47	CO Gas Baseline = all vanes 45° (half-open)	134
48	 All vanes 35° (more than half-open)	121
--	 All vanes 20° (more than half-open)	unstable
49	0°  8 vanes 0° (fully open) 8 vanes 45° (half-open)	98
50	0°  8 vanes 0° (fully open) 8 vanes 45° (half-open)	87
51	0°  8 vanes 0° (fully open) 8 vanes 45° (half-open)	101
52	0°  8 vanes 0° (fully open) 8 vanes 45° (half-open)	95
53	0°  8 vanes 0° (fully open) 8 vanes 45° (half-open)	98

**View from outside the furnace. All vanes set at 45° except as specified.
*Corrected to 500 ppm NH_3^R.

87 ppm (net) from a baseline NO_x^N level of 134 ppm. For all tests in the series, with the exception of the test producing an unstable flame, CO levels were well controlled and less than 200 ppm.

The effect of fuel injector position (depth of insertion) on NO_x formation is shown in Table 6. The burner was equipped with 8 fuel injectors arranged on a circle pattern in the throat. Normal position (7) was 2.5 cm back from the end of the throat, which was minimum insertion to prevent burnback. Positions 6 and 5 were 1.9 cm and 1.3 cm, respectively, back from the end of the throat. As indicated in the table, deeper insertion increased the NO_x formation. It is believed that increasing the penetration depth of the gas injectors altered the flame geometry enhancing the mixing between the products of combustion from the burner and the CO-gas. By contrast, retracting the injector back into the throat defines a more collapsed flame which delays the mixing between the burner products of combustion and CO-gas. Thus reduced conversion of ammonia to NO_x is realized.

TABLE 6. EFFECT OF FUEL INJECTOR POSITION ON NO_x FORMATION

Test	Injector Position	NO_x^{NC}, ppm* (dry, corrected to 3% O_2)
72	7 (2.5 cm from throat)	136
91	5 (1.3 cm from throat)	151
102†	5 (1.3 cm from throat)	140
103†	6 (1.9 cm from throat)	155

*NO_x data corrected to 500 ppm NH_3^R.

†Tests 102 and 103 employed a different injector orientation pattern than test 72 and 91.

The fuel injectors were "chisel tip" spuds with a single orifice on one face of the chisel tip. Normal orientation of the orifice was toward the burner centerline (radially in). The effect of more random orientations of

the injectors, simulating typical field conditions, was tested (tests 102-110 and 134-143). The general result of these tests was that NO_x formation was somewhat less with the more random pattern, however the effectiveness of combustion staging in reducing NO_x (by biasing fuel to selected injectors in this case) was also less. A second injector-orientation test constituted orienting all injector orifices radially outward. This is a method of staging the combustion by fuel biasing. In order to stabilize the flame with the injectors in this orientation, it was necessary to open the air registers basically to 15°, with vanes 1, 5, 9 and 13 at 35° (1 = top, counting clockwise from outside the furnace). As indicated in Table 7, rotation of the fuel injection angle away from the normal radial-inward position to a radial-outward position had a strong effect on the NO_x level. Creating a fuel-rich outer zone in the flame for ammonia destruction apparently was successful. However, as also noted in the table, a high CO level also resulted with the injectors in the radial-outward position. It is probable that an optimum injection angle could be achieved by an intermediate degree of injector rotation which would produce an acceptable CO level while still retaining much of the NO_x reduction effect.

TABLE 7. EFFECT OF INJECTORS RADIALLY OUTWARD ON NO_x FORMATION

Test	Injector Orientation	Vane Settings	NO_x^{NC}, ppm (dry, corr. to 3% O_2)*	CO, ppm (dry)
72	Radially In	All 45°	136	50
112	Radially Out	All 15° Except (1, 5, 9, 13) -35°	23	470

*Corrected to 500 ppm NH_3^R.

In order to test the effect of lower fuel injection velocity, a set of low-velocity injectors was substituted for the normal injectors. The low-velocity injectors differed from the normal injectors only in having larger

injector orifices (0.4763 cm vs. 0.3175 cm diameter). The objective was to achieve some combustion staging via less optimum fuel-air mixing. The low velocity injectors were tested in conjunction with injector orientation changes, insertion depth and fuel bias to selected injectors (Tests 114-142). The key comparison is shown in Table 8, where the effect of the injectors alone is shown with all other variables normal. As indicated in the table, the low-velocity injectors increased the NO_x formation. Among the causes suspected for the observed behavior is that reducing the injection velocity of the gas altered the gas flame geometry. The delayed gas mixing caused more of the fuel to burn on the outer surface of the combustion air stream in the form of a diffusion flame. This is suspected to have caused the flame to expand closer to the furnace wall where CO-gas is present promoting ammonia conversion to NO_x. With increased gas injection velocity, the mixing between the fuel and air was more efficient and as such the flame structure was compact and confined to the center of the furnace. Mixing of the gas flame products of combustion with the CO-gas was thus delayed reducing ammonia conversion to NO_x.

TABLE 8. EFFECT OF LOW-VELOCITY INJECTORS ON NO_x FORMATION

Test	Injector Type	NO_x^{NC}, ppm (dry, corr. to 3% O_2)*
72	Normal	139
114	Low-velocity	159

*NO_x data corrected to 500 ppm NH_3^R.

Of the minor burner modifications, only asymmetric air register settings (for air bias) produced measurable NO_x reduction. However, the viability of maintaining critical vane settings in the field and the effect of changing the firing rate would have to be considered. Low velocity injectors

and fuel aimed radially outward, both of which attempt to create a fuel-rich zone between the bulk of the burner air and the CO-gas, did not appear beneficial.

6.3 STAGED COMBUSTION

Although several of the burner modification approaches discussed in the previous sections were meant to achieve some degree of combustion staging, this section will discuss methods that are designed to achieve more distinct separation of the combustion process into two separate zones. The four staging methods tested included (1) injectors out-of-service (O.O.S.), (2) NO_x ports on the burner wall, (3) an air lance on the burner centerline (center air) and (4) air injected dowstream of the flame basket using a torus-shaped manifold (torus air).

As shown in Figure 11, all staging techniques basically achieve an extension of the NO_x-versus-stoichiometry effect discussed in Section 6.1. Due to the use of second-stage burning for CO control, however, staging enables operation at lower stoichiometries on the main burner. Also, with the exception of the injectors O.O.S. method, staging provides an added dimension of air control so that the burner stoichiometry can be controlled independently of the total furnace air requirement. The level of CO emission from the boiler is also dependent on burner stoichiometry, and the ability of various staging techniques to reduce NO_x without simultaneously increasing the CO level will be a key factor determining their usefulness. The CO level produced by the unstaged burner is shown in Figure 11 versus burner stoichiometry for later comparison to CO characteristics of various staging techniques.

The injectors O.O.S. method of staging is essentially an intra-burner version of the burners-out-of-service (B.O.O.S.) technique that has been highly effective in reducing NO_x in large multi-burner utility boilers. Fuel was discontinued to selected injectors with the same total fuel entering the furnace via the in-service injectors. This created a more fuel-rich combustion zone at the burner and thus was a method of staging. Various injector patterns were tested to locate the best set of injectors through which to

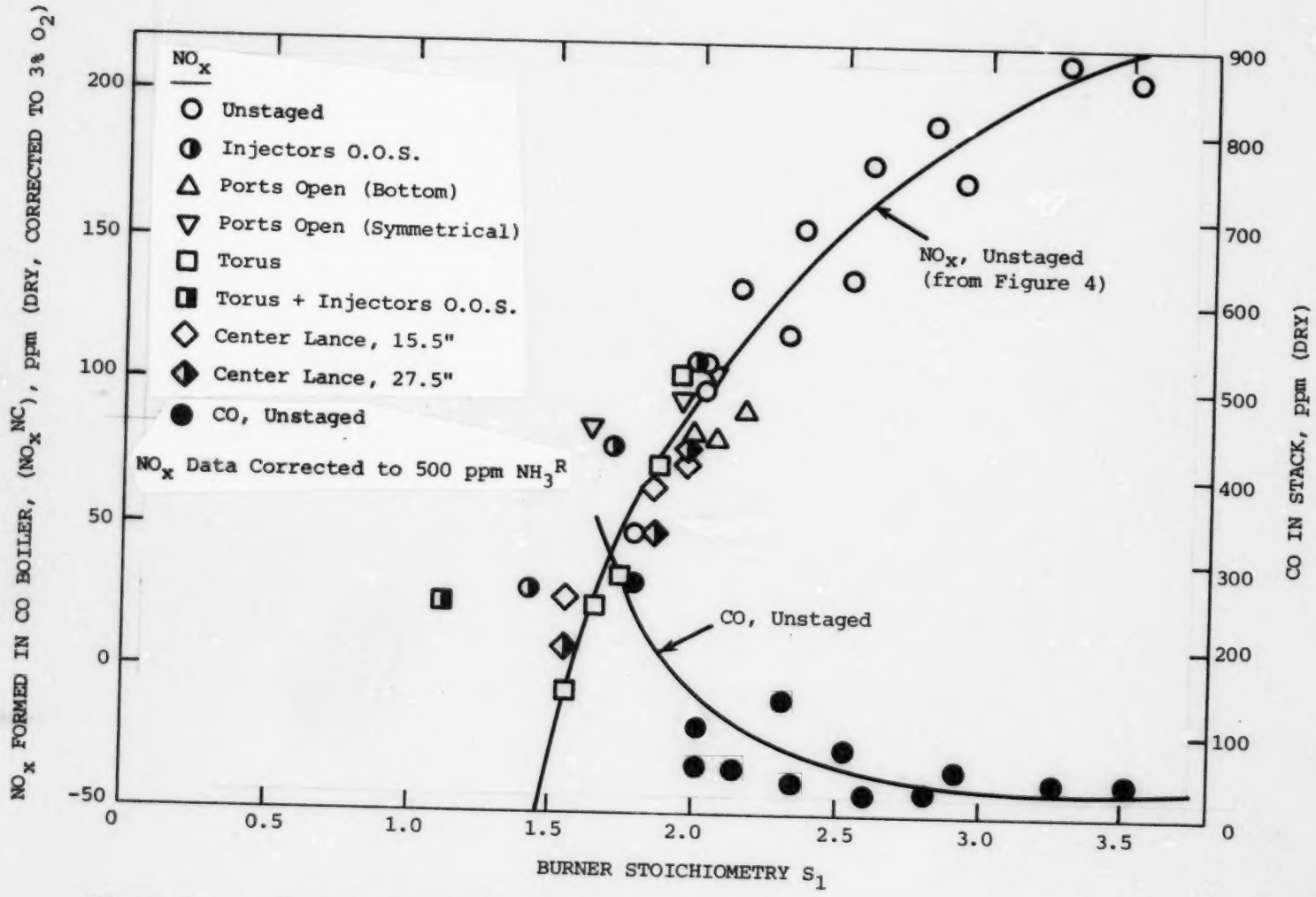


Figure 11. Effect of Burner Stoichiometry on NO_x and CO--Staged and Unstaged Combustion

inject the fuel. The results of the pattern tests are shown in Table 9. Injectors 1-3 on the upper right hand side of the burner taken O.O.S. gave the best results in terms of NO_x reduction without loss of CO control. Moving the O.O.S. pattern one place forward to injectors 2-4 resulted in significant further NO_x reduction but was accompanied by a substantial increase in CO. Continuing to injectors 3-5 resulted in the best NO_x control but another substantial increase in CO. Overall, the pattern tests indicated that the optimum location for injectors O.O.S. is on the right hand side and bottom of the burner with the bottom area providing better NO_x control but having a substantially greater tendency to produce high levels of CO. The tests showed that sheltering the CO-gas from mixing with the combustion air by the uneven distribution of the gas fuel provided a reduction in NO_x.

The laboratory furnace included eight air ports (NO_x ports) in the burner wall arranged on a circle pattern around the burner. Each port was equipped with a conical plug for opening and closing it. When open, the ports admitted air to the furnace directly from the windbox and reduced the amount of air entering via the burner. Similarly to injectors - O.O.S. testing, the NO_x ports were pattern tested to locate the best NO_x port-open pattern. The results of these tests are shown in Table 10. Tests 86 and 87 produced the lowest NO_x levels, indicating that the bottom two or three ports being open was the most effective pattern. CO control was good, with all patterns producing 138 ppm or less CO (see Table 3).

Center air staging employed an air lance on the burner centerline which was supplied by a separate blower. This consisted of a 3.175 cm O.D. tube with 0.07112 cm wall thickness. The depth of immersion of the lance was varied from 39 to 70 cm from the end of the burner throat. Air exited the lance straight ahead, with no radial or swirl velocity component.

Torus air staging employed a torus (donut)-shaped air manifold located 1.68 m from the burner (see Figure 5). The torus injected air radially inward toward the furnace centerline via 32 orifices of 1.43 cm diameter.

The staged combustion test results are shown in Table 11, where unstaged results obtained with nominal NH_3^R levels (~500 ppm) are included for comparison. For the staged combustion tests, the data in Table 3 were

TABLE 9. INJECTORS OUT-OF-SERVICE (O.O.S.) PATTERN TESTS

Test No.	Injectors O.O.S.**	NO_x*	CO$^{\phi}$	Test No.	Injectors O.O.S.**	NO_x*	CO$^{\phi}$
72 Baseline		136	50	61		33	520
54		132	50	62		47	250
55		71	575	63		78	95
56		82	200	64		108	0
57		116	55	65		62	82
58		127	40	66		29	450
59		91	90	67		66	330
60		61	205	68		85	80

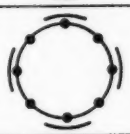
**View from outside furnace

*NO_x^{NC}, ppm (dry, corrected to 3% O_2), corrected to 500 ppm NH_3^R

$^{\phi}$CO data ppm (dry)

Denotes injectors from which fuel is eliminated

TABLE 10. NO_x PORT PATTERN TESTS

Test No.	NO_x Ports Open**	NO_x*	Test No.	NO_x Ports Open**	NO_x*
73	all open	86	82		122
74		91	83		107
75		122	84		96
76		115	85		92
77		112	86		81
78		102	87		82
79		125	88		85
80		108	89	1.27 cm (1/2") open	93
81		100	90	0.635 cm (1/4") open	103

**View from outside furnace

*NO_x^{NC}, ppm (dry, corrected to 3% O_2), corrected to 500 ppm NH_3^R.
(Baseline NO_x (Test 72) = 136 ppm)

Except Tests 89 and 90 - all ports were "fully open) at 5 cm. (2")

Denotes NO_x ports open

TABLE 11. STAGED COMBUSTION TEST RESULTS†

Test No.	Staging Method	Fraction of Air Staged	Burner Stoichiometry (S1)	NO_x^{NC}, ppm (dry, corrected to 3% O_2)*	CO, ppm (dry)
2	Unstaged	0	2.15	134	50
5	Unstaged	0	2.02	108	100
8	Unstaged	0	2.60	178	28
11	Unstaged	0	3.28	215	40
14	Unstaged	0	2.53	137	80
17	Unstaged	0	2.32	118	135
20	Unstaged	0	2.92	172	55
23	Unstaged	0	3.52	208	40
26	Unstaged	0	2.02	97	55
29	Unstaged	0	1.79	48	265
32	Unstaged	0	2.37	155	35
35	Unstaged	0	2.81	191	30
64	Injectors	0.125	2.00	108	0
63	O.O.S.	0.250	1.71	78	95
66		0.375	1.43	29	450
85	Ports Open	0.047	2.17	92	100
86	-Bottom Air	0.090	2.07	81	115
87		0.129	1.99	82	115
88	Ports Open	0.283	1.63	85	115
89	-Symmetrical	0.146	1.95	93	100
90	Air	0.092	2.07	102	83
145		0.119	1.87	71	50
146		0.223	1.66	23	60
147	Torus air	0.268	1.56	-7**	180
168		0.207	1.75	33	150
169		0.120	1.95	113	60
167	Torus + Inj. O.O.S.	0.207 0.375	1.11	23	400
170	Center air	0.178	1.55	27	500
175	-15.5 in (39.4 cm)	0.096	1.85	63	320
176	immersion	0.038	1.97	74	290
172	Center air	0.178	1.55	9	825
174	-27.5 in (69.9 cm)	0.096	1.85	49	300
178	immersion	0.038	1.97	79	160

* Corrected to 500 ppm NH_3^R.
† Full test results in Table 3.
**Negative value indicates NO_x in CO gas was reduced.

modified to reflect actual burner stoichiometries. For tests where staged air was measured, Table 3 already included actual burner stoichiometry and no change was necessary. For the injectors O.O.S. tests and NO_x port-open tests, the amount of staged air had to be estimated and the burner stoichiometry adjusted accordingly. For the injectors O.O.S. tests, each injector O.O.S. was considered to represent 12.5 percent of the total air being staged. The 1-injector, 2-injectors and 3-injectors O.O.S. tests giving lowest NO_x were included in the table. For the NO_x port-open tests, the fraction of air to each port was calculated as:

$$\text{Fraction air staged} = \frac{N * 2.54^2}{11.43^2 + N * 2.54^2} \qquad (2)$$

where

N = Number of ports open (port diameter = 2.54 cm,
burner diameter = 11.43 cm.)

For tests in which ports were less than full open, the effective port area was reduced by 11 percent for 1.27 cm (1/2") open and by 44 percent for 0.635 cm (1/4") open (distance conical plugs were pulled back from port, with "full open" being pulled back 5 cm).

It is important to point out that the data presented in Figures 12 through 15 are based on certain assumptions made in calculating the burner stoichiometry. As such, the accuracy of calculated burner stoichiometry values may not be the same for all the staging methods tested. Low level of accuracy for calculating the burner stoichiometry is suspected for the injector O.O.S. and NO_x port methods since more extensive assumptions were made in performing these calculations. A higher level of confidence exists for data developed using the torus and center lance assemblies since for these methods the staging air was measured rather than calculated.

Figures 12 through 15 compare NO_x and CO characteristics of each staging method to those of unstaged operation (from Figure 11). The injectors O.O.S. method (Figure 12) produced higher NO_x levels than unstaged combustion at stoichiometries below approximately 1.8 but also produced substantially

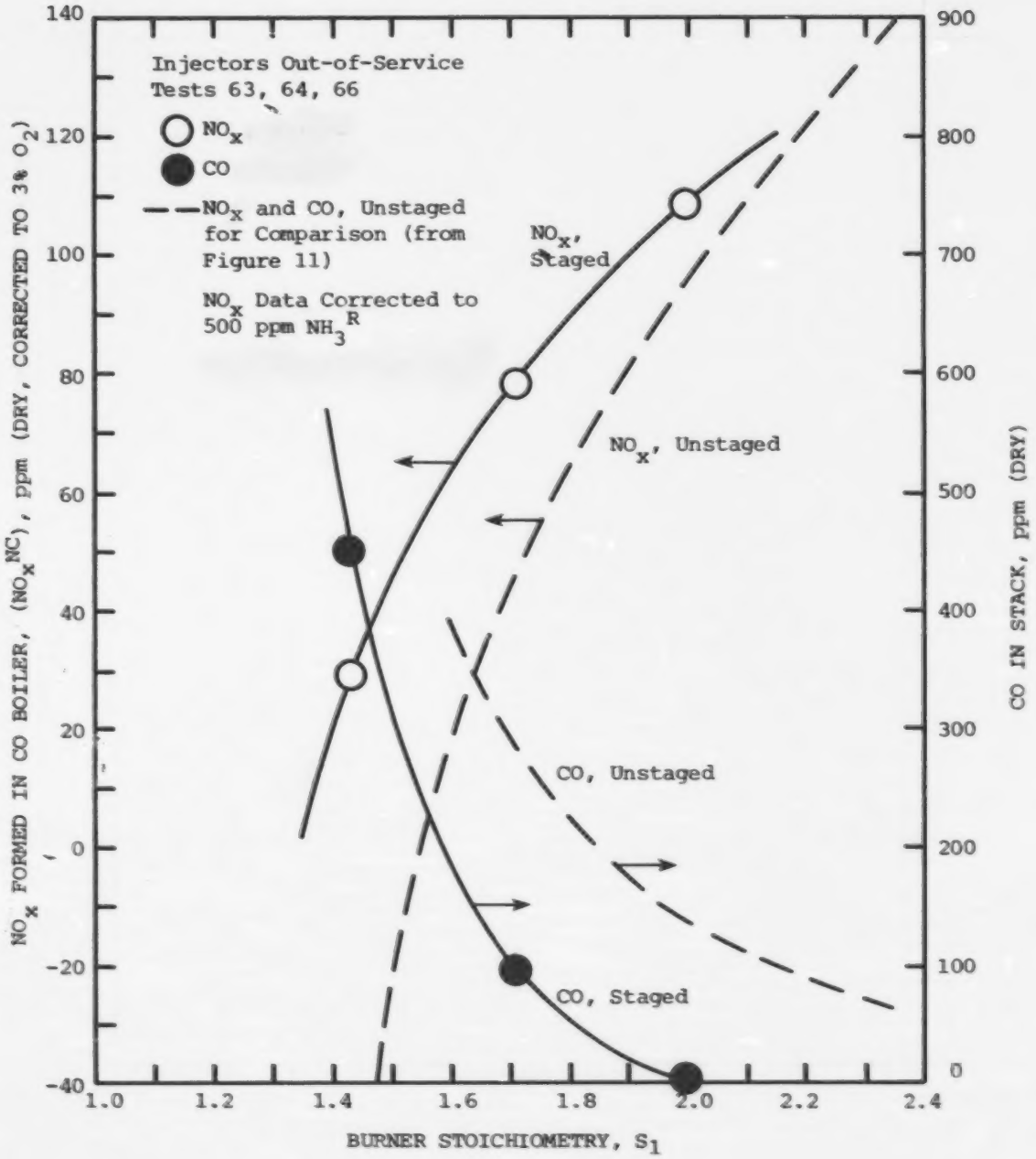


Figure 12. NO_x and CO versus Burner Stoichiometry with Staged Combustion--Injectors Out-of-Service

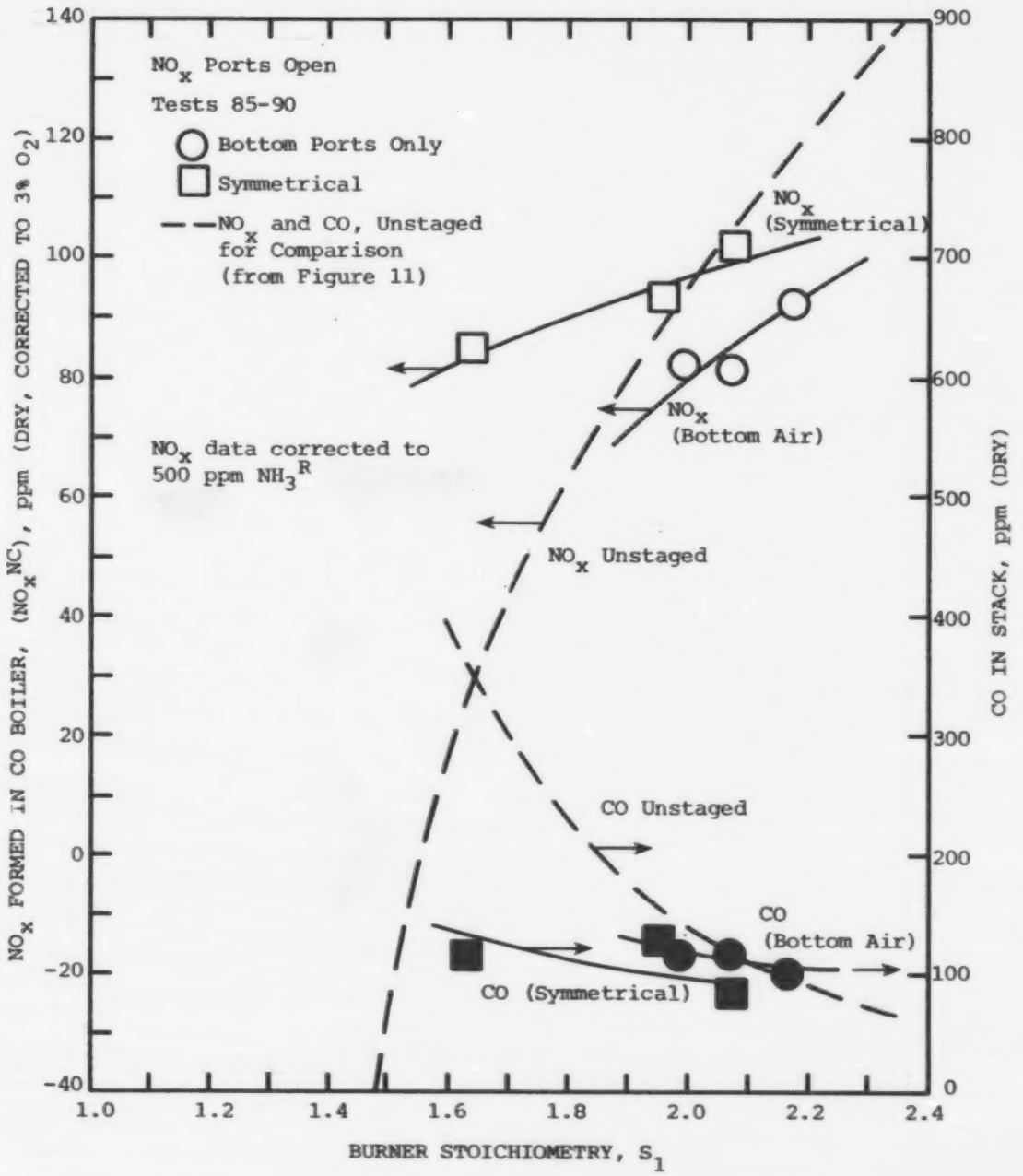


Figure 13. NO_x and CO versus Burner Stoichiometry with Staged Combustion--NO_x Ports Open

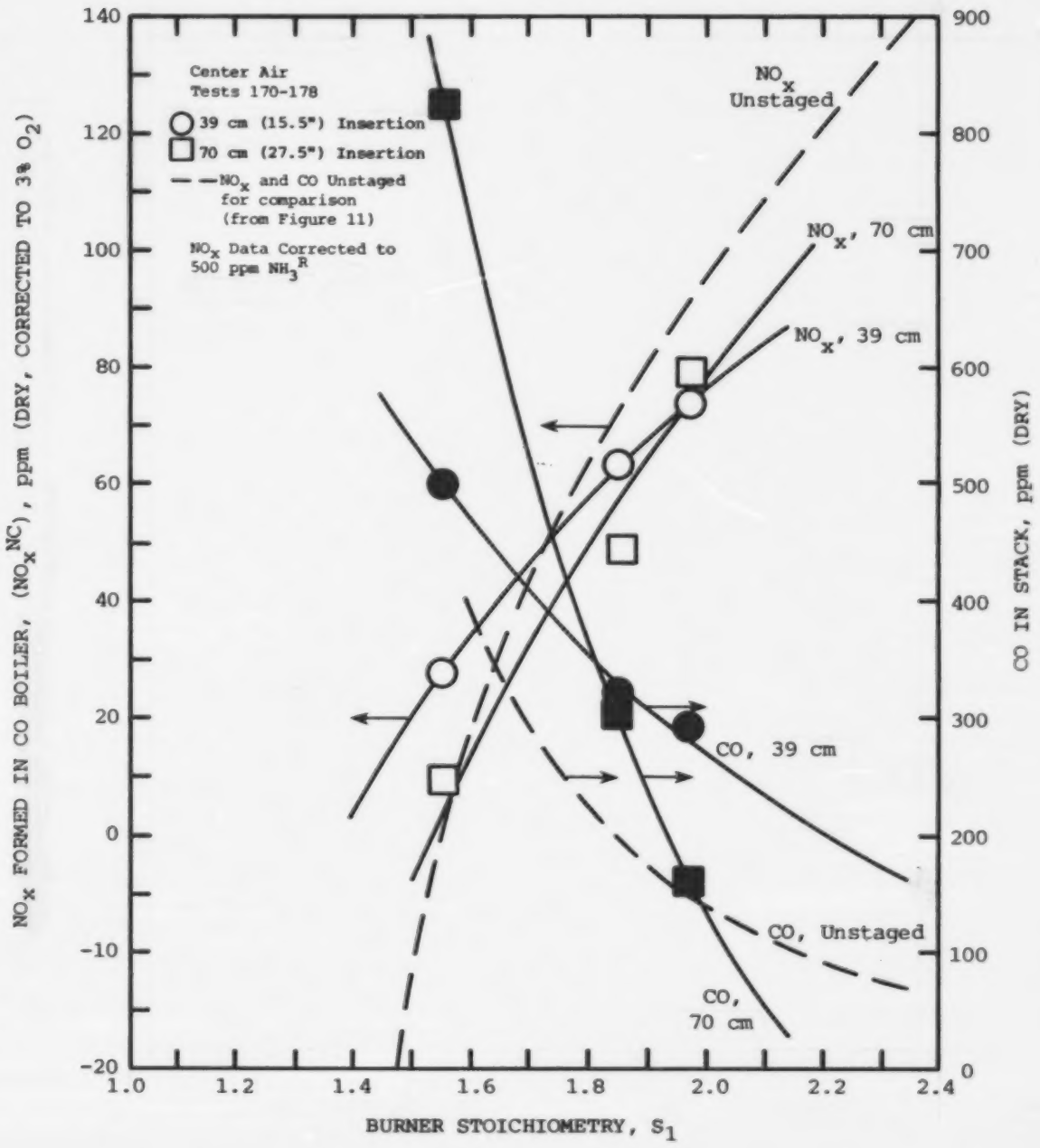


Figure 14. NO_x and CO versus Burner Stoichiometry with Staged Combustion--Center Lance Air

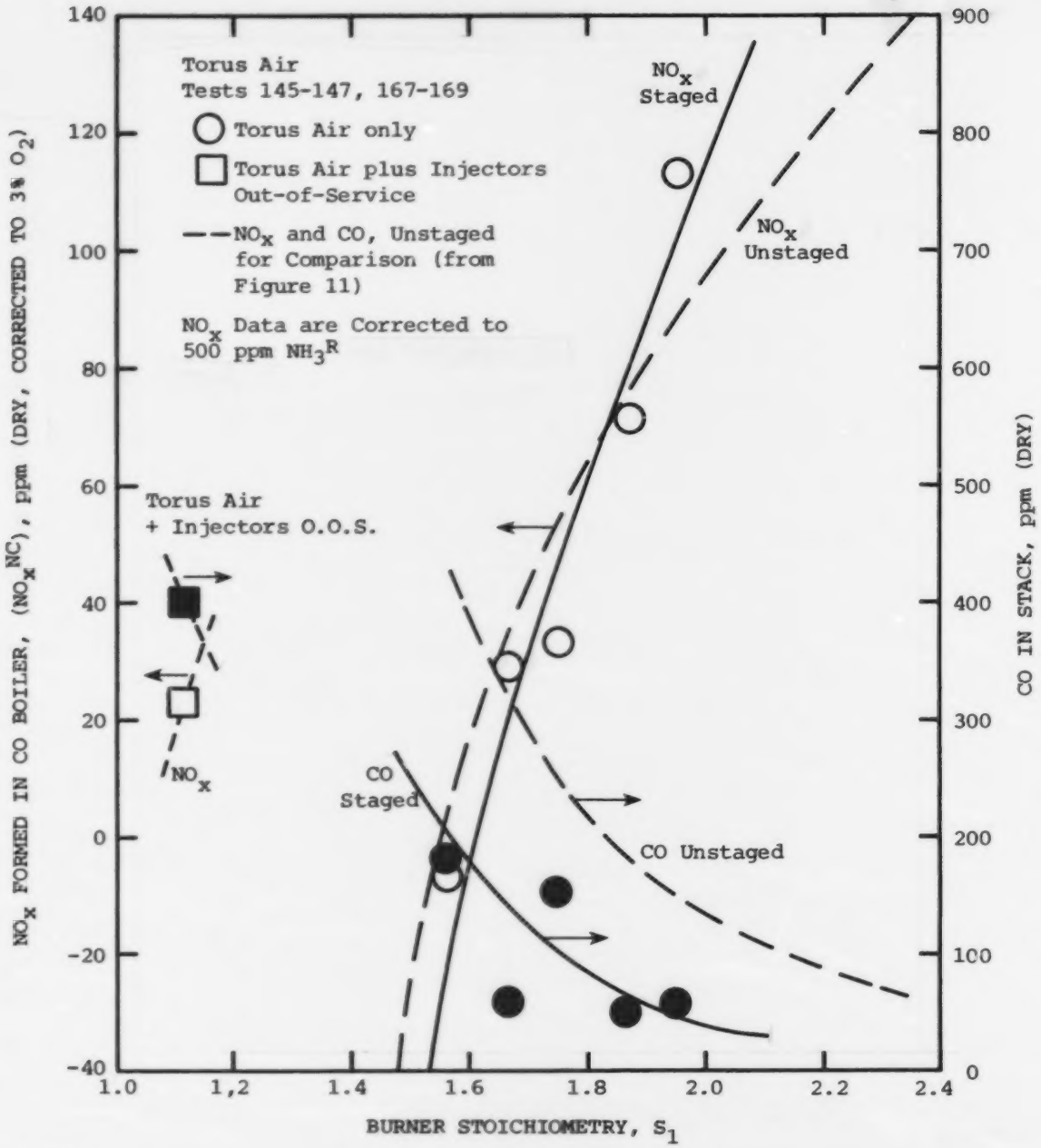


Figure 15. NO_x and CO versus Burner Stoichiometry with Staged Combustion--Torus Air

lower CO levels, enabling operation at lower stoichiometries. The NO_x port-open results (Figure 13) indicate higher NO_x than unstaged operation at stoichiometries below approximately 2.0 for symmetrical air and 1.7 for bottom air. In considering these results for the injectors-out-of-service and NO_x port methods of staging, it should be recalled that calculation of burner stoichiometry for both of these methods is only approximate. Comparisons of NO_x and CO levels at specific stoichiometries to those produced by the unstaged burner may be less meaningful than comparisons of the NO_x-versus-CO characteristics of the various configurations, as will be discussed below.

Use of center air (Figure 14) resulted in very poor CO control, much worse than unstaged operation. Furthermore, NO_x levels were higher than unstaged NO_x levels at stoichiometries below approximately 1.7. The poor CO control probably resulted from the center air being injected straight ahead. The swirl pattern in the furnace was apparently not strong enough to induce sufficient radial progress of the center air to allow it to fully mix with the CO-gas.

Torus air (Figure 15) resulted in NO_x levels comparable to the unstaged burner and better CO control over the full range of stoichiometry tested. This was made possible by location of the air at the outer periphery of the furnace where unoxidized CO-gas would tend to be located plus design of the torus for optimum mixing of the staged air with the CO-gas.

Figure 16 compares the NO_x-versus-CO tradeoffs for the various staging methods tested. Use of torus air gave by far the best results, achieving much lower NO_x formation at comparable CO levels than unstaged combustion or any of the other staging methods. As indicated in the figure, the data indicate that using torus air, the laboratory boiler can be operated with zero net NO_x formation at a CO level of approximately 170 ppm. Very limited data on operation with bottom NO_x ports open indicated that this technique also may have very good NO_x-versus-CO characteristics. NO_x port air would not, however, appear to be as effective as torus air.

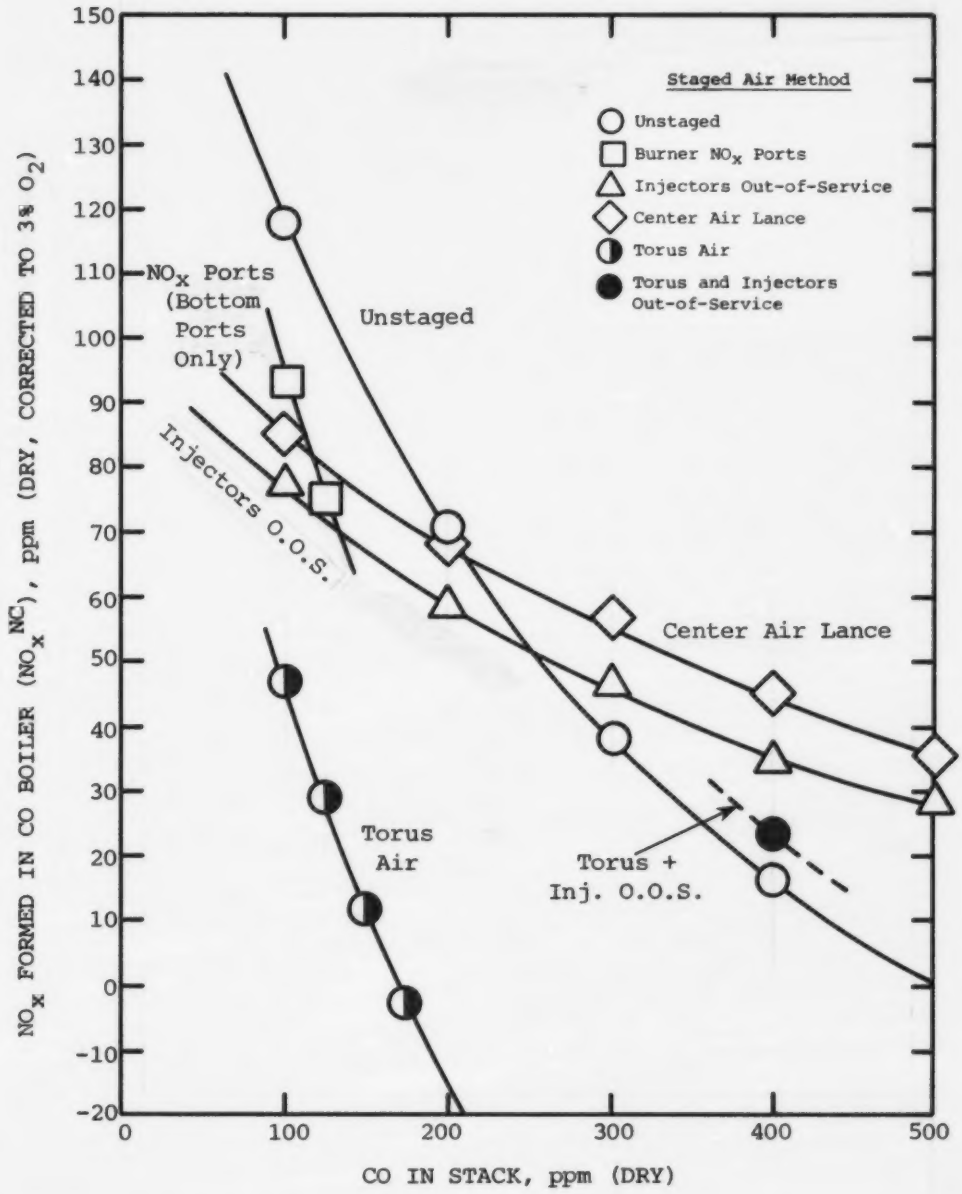


Figure 16. NO_x versus CO for Various Methods of Staging the Combustion

6.4 MAJOR BURNER MODIFICATIONS

Two types of burner modifications were tested that would require substantial hardware changes to implement on a full-scale boiler. These were fuel relocation and modification of throat design.

The first type of fuel relocation tested was relocation of alternate gas injectors outboard of the burner. Injectors 1, 3, 5 and 7 were relocated to NO_x ports around the burner. In this configuration half the fuel entered the furnace via the NO_x ports rather than via the burner throats. As shown in Table 12, this method did not reduce the NO_x, and in fact increased it.

TABLE 12. EFFECT OF FUEL RELOCATION OUTBOARD OF BURNER

Test	Fuel Location	NO_x^{NC}, ppm (dry, corrected to 3% O_2)*	CO, ppm (dry)
157	Normal	110	85
156	Injectors 1, 3, 5, 7 Relocated to NO_x ports	116	75

*Corrected to 500 ppm NH_3^R.

The second type of fuel relocation tested involved diversion of a portion of the fuel from the burner to the CO-gas upstream of the furnace. From 25 to 100 percent of the fuel was diverted to the CO-gas. As shown in Table 13 this fuel relocation increased the NO_x.

TABLE 13. EFFECT OF DIVERTING FUEL TO CO-GAS

Test	Fuel Diverted to CO-Gas, %	NO_x^{NC}, ppm (dry, corrected to 3% O_2)*	CO, ppm (dry)
157	0	110	85
158	25	129	55
159	50	142	55
160	75	141	55
161	100	135	55

*Corrected to 500 ppm NH_3^R.

Two throat design modifications were tested. The first was an elongated version of the original divergent throat, and the second was a straight throat (non-divergent) of the original length. Figure 17 illustrates these two throat modifications. The results of the tests for both throat modifications are shown in Table 14. Each modified throat design was tested in normal firing and also with injectors 2-4 O.O.S. and with maximum injector insertion depth. The results showed that both throat design modifications increased NO_x both with and without injectors O.O.S.

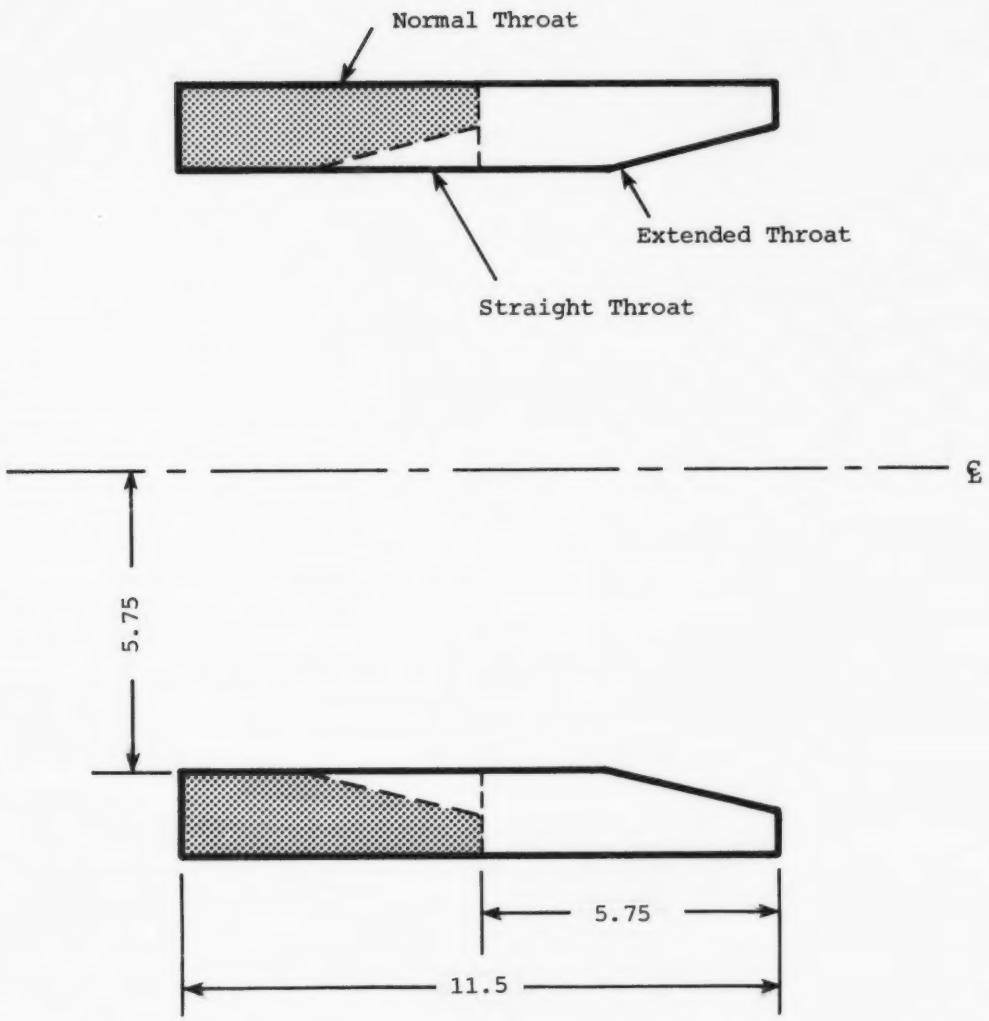


Figure 17. Burner Throat Modifications
(dimensions in centimeters)

TABLE 14. EFFECT OF BURNER THROAT DESIGN MODIFICATIONS

Test No.	Throat Design	Injectors O.O.S.	Injector Insertion	NO_x^{NC}, ppm (dry, corr. to 3% O_2)*	CO, ppm (dry)
62	Normal	2-4	7	47	250
157	Normal	None	7	110	85
179	Elongated	2-4	M	71	120
180	Elongated	2-4	7	83	100
181	Elongated	None	7	132	55
182	Straight	2-4	7	92	230
183	Straight	2-4	M	118	80
184	Straight	None	7	154	50

*Corrected to 500 ppm NH_3^R.

SECTION 7.0

SELECTION OF BEST NO_x REDUCTION APPROACHES

Staging the combustion using torus air was clearly the best NO_x reduction approach tested in the laboratory. This method produced substantial NO_x reductions without sacrificing CO control. Air staging using a center air lance located on the burner axis was not as successful due to a tendency to produce high CO levels. Staged air admitted via ports located around the burner also appeared promising especially using ports located below the burner; however, this method did not show potential to be as effective as torus air.

In the field, torus air translates to injection of staged combustion air well downstream of the burner transverse to the overall furnace flow. This could be accomplished by a torus, as was done in the laboratory, or by ports in the furnace enclosure. Side ports alone may or may not be sufficient. It is possible that top and bottom ports would be required as well. Center air could be used as an adjunct to torus air, particularly for a furnace having low L/D.

Asymmetric air register settings to bias the air works reasonably well (single-burner furnace was tested) but would be difficult to deploy on a consistent basis in the field. The best adjustment may vary with boiler load, which would be difficult to accomplish.

Injectors O.O.S. has a significant effect on NO_x; however, this method leads to high CO. NO_x-versus-CO characteristics would have to be verified over a load range on any particular unit. This method may be of value where modest NO_x reduction is required.

Modification of fuel gas injection angle and velocity showed a strong effect on NO_x. Although optimum conditions were not reached, this method probably deserves more exploration.

SECTION 8.0

CONCLUSIONS

This section presents major conclusions drawn from the results of the laboratory testing. In reviewing these conclusions it should be considered that the tests were performed on a single-burner, horizontal furnace with CO gas admitted via a concentric annulus surrounding the burner throat. All tests were on natural gas fuel. The ratio of CO-gas to total stack gas was approximately 0.65 (dry basis). The CO-gas contained approximately 2 percent CO, 500 ppm ammonia and 120 ppm NO_x. Some of the conclusions may be very specific to some of these test conditions and others may be more general.

1. All the test program objectives were achieved: the laboratory model was shown to accurately reproduce the emission characteristics of a full-scale CO boiler, the effect of operating variables was determined and several promising combustion modifications for NO_x reduction were identified.

2. NO_x formed in the CO boiler is mainly due to conversion of ammonia entering with the CO-gas.

3. The most important variables influencing the NO_x level are the ammonia content of the CO-gas and the burner stoichiometry (air/fuel ratio).

4. Conversion of ammonia to NO_x is normally (without staging) in the range of 10 to 55 percent, depending on burner stoichiometry.

5. Part of the NO_x entering with the CO-gas is destroyed in the furnace, with the survival rate normally being approximately 75 percent but dropping to as low as approximately 10 percent with reduction in burner stoichiometry.

6. Air staging was found to be the best NO_x control method. Addition of staged air well downstream of the burner with good cross-mixing produces the best results.

7. Asymmetric air register setting to bias the air is reasonably effective but would be difficult to implement in the field.

8. Taking fuel injectors out of service (multi-spud burner) can produce modest NO_x reductions but tends to cause high CO. CO characteristics at various loads could be a problem with this technique.

9. Fuel injection angle and velocity have substantial effects on NO_x, and it appears possible to optimize these variables for lower NO_x operation.

10. Staged air ports located around the burner are basically effective with ports located below the burner being most effective. Overall, however, NO_x ports are less effective than downstream air staging using the method described in Item 5 above.

11. NO_x reduction approaches that are ineffective include diversion of fuel outboard of the burner or to the CO-gas, less divergent burner throat and extended burner throat.

SECTION 9.0

RECOMMENDATIONS

The laboratory work has demonstrated that air staging is the best approach of those evaluated for NO_x control on refinery CO boilers. Optimization of fuel injection velocity and orientation is a secondary approach that could complement staging.

1. Air staging should be demonstrated on a full-scale refinery CO boiler. The full-scale demonstration should be designed to achieve similar temperature-time-stoichiometry conditions to those found effective in the laboratory. Staged air addition should be primarily transverse to furnace gas flow well downstream of the burner and should be designed for optimum mixing as done in the laboratory. It should be noted that similar air staging on refinery CO boilers has not performed well in the past, perhaps due to lack of knowledge of the correct design parameters. Proper placement of the second stage air and design for adequate mixing are critical to the success of this method.

2. Fuel injection velocity and orientation had a substantial effect on NO_x emissions in the laboratory, and these variables should be optimized in conjunction with air staging.

3. Successful application of air staging to a unit that is substantially different in design or operation than that tested in the laboratory may require further laboratory testing to determine correct design conditions. Major departures in the ratio of CO-gas to stack gas, CO-gas entry relative to the burner(s), CO-gas composition and/or burner fuel (possibly oil) from conditions tested in the laboratory would probably require further laboratory optimization.

APPENDIX A

FLOW METER EQUATIONS

The following equations were used to calculate fuel, air and flue gas flow rates based on raw flow meter readings.

Fuel to CO-Gas Generator

$$W_1 = 4.51\ R \sqrt{\frac{P + 14.7}{TF + 460}} \qquad \text{(A-1)}$$

CO-Gas Flow

$$W_2 = 17{,}234 \sqrt{\frac{DP}{TF + 460}} \qquad \text{(A-2)}$$

Air to CO-Gas Generator

$$W_3 = W_2 - W_1 \qquad \text{(A-3)}$$

Fuel to CO Boiler

$$W_4 = 1.365\ R \sqrt{\frac{P + 14.7}{TF + 460}} \qquad \text{(A-4)}$$

Air to CO Boiler

$$W_5 = 16{,}091 \sqrt{\frac{DP}{TF + 460}} \qquad \text{(A-5)}$$

where

W = kg/hr

R = rotameter reading, %

P = rotameter pressure, psig

TF = flowmeter temperature, °F

DP = venturi pressure drop, I.W.G.

Calculation of air to ports around the burners when open was based on area ratio using a 11.43 cm burner diameter and 2.54 cm port diameter. In some tests, ports were partially open. Geometric analysis indicated that for these tests, where ports were 1.27 cm open, flow was reduced by 11 percent; and where ports were 0.635 cm open, flow was reduced by 44 percent.

Measurements of staged air flows to the torus and center lance were made using calibrated rotameters.

APPENDIX B

TEST DATA

The raw test data for the 205 tests conducted after equipment shake-down was completed are presented in Tables B-1 and B-2. Table B-1 contains data from the CO-gas generator, and Table B-2 contains data from the CO boiler.

The following list explains the abbreviations and comments in the Tables.

Abbreviations Used in Tables:

DP	Flow meter differential pressure
IWG	Inches water gage
TEMP	Temperature
RDG	Reading
Flow %	Flow meter reading, %
Flow psig	Flow meter pressure
MAIN AIR	Refers to main air flow meter
INJ. OOS	Fuel injectors out-of-service (fuel shut off)
INJ. POSIT.	Fuel injector position (retraction back from end of throat)
INJ. ORIENT	Fuel injector orientation (rotational)
RI	Radially inward
PP	Plant patttern (as found on full scale test boiler--apparently random)
RO	Radially outward

Comments:

NH3 measurements	Tests during which NH_3 in the CO-gas was being measured.
Swirl - 1 - 16 = 35	Burner air swirl variation, vanes 1 through 16 set at 35°.
Ports = 1 - 8 - 1"	NO_x ports 1 through 8 open one inch. (Valve stem retraction - see Figure 4.)

TABLE B-1. CO GAS GENERATOR DATA

DATE	TEST #	GAS FLOW METER DP (IWG)	METER TEMP. F.	FUEL FLOW RDG Z	FUEL FLOW TEMP. F.	AIR TEMP. F.	NH3 Z	NH3 FLOW PSIG	GAS COMPOSIT. (DRY) NOX PPM	O2 Z	CO Z	CO2 Z
3/29	1	4.25	1266	53.7	94	85	0	4.5	115	0	2.1	10.5
3/29	2	4.25	1263	53.5	95	86	60	4.5	117	0	2.1	10.5
3/29	3	4.25	1261	53.5	96	87	75	4.5	115	0	2.1	10.4
3/29	4	4.25	1280	51.5	97	86	75	3.5	107	0	1.5	11.0
3/29	5	4.2	1281	51.5	98	87	60	3.5	112	0	1.7	11.0
3/29	6	4.2	1280	51.5	97	87	0	3.5	105	0	1.5	11.0
3/29	7	4.2	1232	55	96	86	0	3.2	118	0	3.2	9.9
3/29	8	4.15	1222	55	97	86	60	3.2	109	0	3.35	9.7
3/29	9	4	1205	55	97	87	75	3.2	115	0	3.6	9.55
3/29	10	3.9	1186	57	95	86	75	3.2	115	0	4.7	8.85
3/29	11	3.85	1178	57	94	88	60	3.2	110	0	4.7	8.9
3/29	12	3.85	1176	57	95	88	0	3.2	110	0	4.75	8.9
4/8	13	4.25	1267	53.5	86	85	0	4.5	109	0	2.1	10.4
4/8	14	4.25	1262	53.5	86	85	60	4.5	113	0	2.2	10.3
4/8	15	4.25	1259	53.5	87	85	75	4.5	117	0	2.2	10.3
4/8	16	4.3	1289	51	88	85	75	4.5	115	0	1.4	11.0
4/8	17	4.3	1292	51	89	86	60	4.5	115	0	1.39	11.0
4/8	18	4.3	1294	51	89	86	0	4.5	117	0	1.4	11.0
4/8	19	4.15	1244	55	90	87	0	3.9	120	0	3	9.8
4/8	20	4.15	1236	55	90	87	60	3.5	115	0	3	9.8
4/8	21	4.15	1234	55	90	89	75	3.5	118	0	3	9.8
4/8	22	4.1	1220	57	91	89	75	3.5	111	0	3.7	9.2
4/8	23	4.1	1212	57	91	88	60	3.5	115	0	3.8	9.2
4/8	24	4.1	1207	57	91	88	0	3.5	114	0	3.85	9.2
4/11	25	4.3	1271	53	80	80	0	6.5	112	0	2.1	10.4
4/11	26	4.35	1273	53	81	80	60	6.5	112	0	2.1	10.4
4/11	27	4.35	1273	53	80	78	75	6.5	115	0	2.1	10.4
4/11	28	4.35	1317	51	81	81	75	4	109	0	1.3	11.2
4/11	29	4.35	1313	51	81	80	60	4.5	115	0	1.2	11.2
4/11	30	4.35	1313	51	81	80	0	4.5	115	0	1.3	11.2
4/11	31	4.3	1270	55	80	79	0	4.2	112	0	3	9.8
4/11	32	4.3	1255	55	80	78	60	4	115	0	3.1	9.8
4/11	33	4.3	1249	55	80	79	75	4	116	0	3	9.8
4/11	34	4.25	1231	57	81	80	75	3.9	115	0	3.7	9.3
4/11	35	4.25	1228	57	81	79	60	3.9	119	0	3.7	9.3
4/11	36	4.25	1225	57	81	80	0	3.5	116	0	3.7	9.35
4/11	37	4.3	1272	53	82	82	60	7	150	0	2.1	10.4
4/11	38	6	1199	65.5	82	81	60	3.5	120	0	2.4	10.4
4/11	39	4.3	1270	53	81	79	60	3.5	119	0	2.1	10.4
4/11	40	4.25	1255	53	82	79	150	5	115	0	2.1	10.4
4/11	41	4.3	1258	53	83	80	60	3.9	48	0	2.1	10.5
4/14	42	4.2	1247	53	94	86	0	3.5	119	0	2.2	10.3
4/14	43	4.25	1251	53	92	85	60	3.5	111	0	2.2	10.3
4/14	44	4.25	1253	53	93	86	75	3.5	115	0	2.2	10.4
4/15	45	4.3	1303	51	93	90	60	3.5	115	0	1.4	11.0
4/15	46	4.2	1210	57	95	92	60	3.5	111	0	3.8	9.2
4/18	47	4.4	1245	51.5	83	81	60	4.5	118	0	2.1	10.3
4/18	48	4.4	1243	51.5	86	83	60	4.5	119	0	2.2	10.3
4/18	49	4.3	1237	51.5	88	86	60	4.5	120	0	2.2	10.3
4/18	50	4.3	1233	51.5	91	86	60	4.5	120	0	2.3	10.2

TABLE B-1. (CONTINUED)

DATE	TEST #	GAS FLOW METER DP (IWG)	GAS FLOW METER TEMP. F.	FUEL FLOW RDG Z	FUEL FLOW TEMP. F.	AIR TEMP. F.	NH3 FLOW Z	NH3 FLOW PSIG	GAS COMPOSIT. (DRY) NOX PPM	O2 Z	CO Z	CO2 Z
4/18	51	4.35	1229	51.5	94	89	60	3.5	113	0	2.1	10.2
4/18	52	4.35	1227	51.5	94	87	60	3.5	115	0	2.3	10.2
4/18	53	4.35	1226	51.5	95	88	60	3.5	115	0	2.3	10.2
4/18	54	4.4	1220	51.5	96	88	60	3.5	118	0	2.2	10.2
4/18	55	4.35	1225	51.5	96	89	60	3.5	112	0	2.3	10.2
4/18	56	4.35	1225	51.5	97	86	60	3.5	112	0	2.2	10.2
4/18	57	4.35	1222	61.5	97	87	60	3.5	118	0	2.1	10.3
4/18	58	4.35	1223	51.5	98	87	60	3.5	120	0	2.1	10.3
4/18	59	4.35	1224	51.5	97	86	60	3.5	115	0	2.2	10.2
4/18	60	4.35	1224	51.5	96	86	60	3.5	116	0	2.2	10.3
4/18	61	4.35	1224	51.5	95	87	60	3.5	110	0	2.3	10.2
4/18	62	4.4	1224	51.5	95	85	60	3.5	112	0	2.5	10.2
4/18	63	4.4	1223	51.5	94	86	60	3.5	120	0	2.5	10.2
4/18	64	4.4	1223	51.5	94	86	60	3.5	120	0	2.4	10.2
4/19	65	4.5	1228	51.5	98	90	60	4	115	0	2.4	10.3
4/19	66	4.45	1226	51.5	99	90	60	4	117	0	2.4	10.2
4/19	67	4.45	1227	51.5	98	90	60	4	118	0	2.3	10.2
4/19	68	4.45	1229	51.5	98	89	60	4	118	0	2.4	10.2
4/19	69	4.45	1227	51.5	99	89	60	3.5	78	0	2.2	10.3
4/19	70	4.45	1227	51.5	99	88	60	3.5	79	0	2.15	10.3
4/19	71	4.45	1227	51.5	98	88	60	3.5	78	0	2.3	10.2
4/19	72	4.5	1238	51.5	90	85	60	4.5	112	0	2.15	10.3
4/19	73	4.5	1236	51.5	91	86	60	4.5	119	0	2.2	10.3
4/19	74	4.5	1232	51.5	92	87	60	4.5	120	0	2.3	10.2
4/19	75	4.45	1232	51.5	93	88	60	4.5	120	0	2.2	10.3
4/19	76	4.5	1233	51.5	96	89	60	4.5	120	0	2.1	10.3
4/19	77	4.5	1236	51.5	96	88	60	4.5	118	0	2.15	10.3
4/19	78	4.5	1237	51.5	96	8	60	4.5	118	0	2.1	10.3
4/19	79	4.5	1236	51.5	96	88	60	4.5	119	0	2.1	10.2
4/19	80	4.5	1237	51.5	95	88	60	4.5	112	0	2.1	10.4
4/19	81	4.5	1236	51.5	96	88	60	4.5	115	0	2.1	10.3
4/19	82	4.5	1235	51.5	95	88	60	4.5	115	0	2.1	10.4
4/19	83	4.5	1236	51.5	96	88	60	4.5	115	0	2.1	10.3
4/19	84	4.5	1237	51.5	95	87	60	4.5	115	0	2.1	10.3
4/19	85	4.5	1236	51.5	95	88	60	4.5	118	0	2.2	10.3
4/19	86	4.5	1234	51.5	95	88	60	4.5	119	0	2.2	10.3
4/19	87	4.5	1231	51.5	96	89	60	4.5	117	0	2.2	10.3
4/19	88	4.5	1229	51.5	97	89	60	4.5	120	0	2.15	10.3
4/19	89	4.5	1226	51.5	97	90	60	4.5	115	0	2.3	10.2
4/19	90	4.5	1228	51.5	97	90	60	4	115	0	2.4	10.2
4/20	91	4.3	1251	52	87	81	60	4.5	115	0	2.1	10.3
4/20	92	4.2	1247	52	88	82	60	4.5	120	0	2.2	10.2
4/20	93	4.3	1248	52	89	83	60	4.5	120	0	2.2	10.2
4/20	94	4.3	1246	51	89	84	60	4	120	0	2.2	10.2
4/20	95	0	0	0	0	0	60	4	0	0	0	0
4/20	96	4.3	1247	52	90	83	60	4	120	0	2.05	10.4
4/20	97	4.3	1248	52	89	82	60	4	120	0	2.2	10.3
4/20	98	4.35	1248	52	89	81	60	4	115	0	2.2	10.3
4/20	99	4.3	1246	52	89	82	60	4	118	0	2.3	10.2
4/20	100	4.3	1245	52	90	83	60	4	119	0	2.2	10.2
4/20	101	4.35	1244	52	90	83	75	4	118	0	2.2	10.2

TABLE B-1. (CONTINUED)

DATE	TEST #	GAS FLOW METER DP (IWG)	GAS FLOW METER TEMP. F.	FUEL FLOW RDG %	FUEL FLOW TEMP. F.	AIR TEMP. F.	NH3 FLOW %	NH3 FLOW PSIG	GAS COMPOSIT. (DRY) NOX PPM	O2 %	CO %	CO2 %
4/20	102	4.35	1243	52	90	83	60	3.5	113	0	2.3	10.3
4/20	103	4.3	1236	52	91	84	60	3.5	119	0	2.5	10.1
4/20	104	4.3	1234	52	91	84	60	3.5	121	0	2.4	10.2
4/20	105	4.3	1238	52	91	84	60	3.5	117	0	2.4	10.1
4/20	106	4.3	1234	52	91	85	60	3.5	118	0	2.4	10.1
4/20	107	4.25	1235	52	92	84	60	3.5	116	0	2.4	10.2
4/20	108	4.25	1234	52	92	85	60	3.5	119	0	2.4	10.2
4/20	109	4.25	1234	52	92	84	60	3.5	116	0	2.4	10.1
4/20	110	4.25	1234	52	92	85	60	3.5	117	0	2.45	10.2
4/21	111	4.4	1252	52	88	83	60	4.3	118	0	2.2	10.2
4/21	112	4.35	1231	52	86	81	60	3.5	120	0	2.4	10.2
4/21	113	4.35	1232	52	87	82	60	3.5	115	0	2.4	10.1
4/21	114	4.3	1233	52	89	86	60	4	114	0	2.2	10.3
4/21	115	4.3	1234	52	90	86	60	4	115	0	2.35	10.1
4/21	116	4.3	1234	52	90	85	60	4	119	0	2.3	10.3
4/21	117	4.25	1233	52	91	87	60	4	120	0	2.4	10.2
4/21	118	4.2	1231	52	91	87	60	3.9	119	0	2.5	10.1
4/21	119	4.3	1231	52	91	86	60	3.9	122	0	2.3	10.2
4/22	120	4.4	1223	52	85	83	60	3.5	115	0	2.3	10.3
4/21	121	4.4	1224	52	86	83	60	3.5	117	0	2.3	10.2
4/22	122	4.4	1222	52	88	84	60	3.5	119	0	2.4	10.1
4/22	123	4.4	1224	52	87	84	60	3.5	115	0	2.4	10.2
4/22	124	4.4	1228	52	88	85	60	3.5	115	0	2.3	10.2
4/22	125	4.4	1226	52	89	85	60	3.5	120	0	2.4	10.1
4/22	126	4.4	1229	52	89	87	60	3.5	119	0	2.3	10.3
4/22	127	4.4	1224	52	89	85	60	3.5	115	0	2.4	10.2
4/22	128	4.4	1222	52	89	84	75	3.5	120	0	2.3	10.3
4/22	129	4.4	1226	52	89	85	0	3.5	123	0	2.2	10.2
4/22	130	4.4	1225	52	90	87	60	3.5	119	0	2.3	10.3
4/22	131	4.3	1223	52	91	85	60	3.5	120	0	2.2	10.3
4/22	132	4.35	1223	52	92	86	60	3.5	115	0	2.2	10.2
4/22	133	4.35	1218	52	94	88	60	3.5	112	0	2.3	10.2
4/22	134	4.4	1223	52	94	88	60	3.5	115	0	2.1	10.4
4/22	135	4.4	1226	52	95	87	60	3.5	113	0	2.1	10.4
4/22	136	4.45	1227	52	94	86	60	3.5	112	0	2	10.4
4/22	137	4.45	1228	52	94	87	60	3.5	112	0	2.1	10.4
4/22	138	4.45	1229	52	93	86	60	3.5	118	0	2.2	10.4
4/22	139	4.45	1227	52	94	87	60	3.5	115	0	2.2	10.3
4/22	140	4.45	1226	52	94	88	60	3.5	115	0	2.2	10.3
4/22	141	4.45	1227	52	94	87	60	3.5	119	0	2.1	10.3
4/22	142	4.4	1226	52	94	88	60	3.5	117	0	2.2	10.3
4/25	143	4.3	1229	52	93	86	60	4	129	0	2.2	10.3
4/25	144	4.3	1229	52	94	88	60	4	120	0	2.1	10.3
4/27	145	4.4	1220	52	88	83	60	3.5	120	0	2.4	10.1
4/27	146	4.35	1220	52	89	84	60	3.5	115	0	2.4	10.1
4/27	147	4.35	1218	52	91	83	60	3.5	120	0	2.4	10.2
4/27	148	4.35	1219	52	92	83	60	3.5	120	0	2.3	10.3
4/27	149	4.3	1218	52	93	86	60	3.5	120	0	2.4	10.3
4/27	150	4.3	1217	52	93	86	60	3.5	121	0	2.35	10.3

TABLE B-1. (CONTINUED)

DATE	TEST #	GAS FLOW METER DP (IWG)	GAS FLOW METER TEMP. F.	FUEL FLOW RDG Z	FUEL FLOW TEMP. F.	AIR TEMP. F.	NH3 FLOW Z	NH3 FLOW PSIG	GAS COMPOSIT. (DRY) NOX PPM	O2 Z	CO Z	CO2 Z
4/27	151	4.3	1217	52	93	85	60	3.5	120	0	2.3	10.3
4/27	152	4.4	1220	52	95	89	60	3.5	120	0	2.4	10.2
4/27	153	4.4	1220	52	95	89	60	3.5	120	0	2.4	10.2
4/27	154	4.4	1220	52	95	89	60	3.5	120	0	2.4	10.2
4/27	155	4.4	1220	52	95	89	60	3.5	120	0	2.4	10.2
5/2	156	4.05	1239	52.5	88	84	60	3.5	120	0	2.2	10.2
5/2	157	4.05	1236	52.5	88	86	60	3.5	115	0	2.4	10.2
5/2	158	4	1240	52.5	89	85	60	3.5	115	0	2.4	10.1
5/2	159	4	1243	52.5	90	86	60	3.5	119	0	2.3	10.1
5/2	160	4	1240	52.5	91	87	60	3.5	119	0	2.4	10.1
5/2	161	4	1231	52.5	92	88	60	3.5	125	0	2.4	10.1
5/2	162	4	1244	52.5	93	86	60	3.5	115	0	2.3	10.3
5/2	163	4	1244	52.5	93	86	60	3.5	115	0	2.3	10.3
5/2	164	4	1244	52.5	93	86	60	3.5	115	0	2.3	10.3
5/2	165	4	1240	52.5	92	87	60	3.5	115	0	2.4	10.2
5/2	166	4	1238	52.5	93	88	60	,5	115	0	2.3	10.3
5/3	167	3.95	1224	52.5	90	87	60	3.5	125	0	2.4	10.2
5/3	168	3.95	1218	52.5	91	87	60	,5	135	0	2.3	10.2
5/3	169	3.95	1228	52.5	94	92	60	3.5	105	0	2.4	10.2
5/3	170	3.95	1210	52.5	95	90	60	3	112	0	2.3	10.2
5/3	171	3.95	1210	52.5	95	90	60	3	112	0	2.3	10.2
5/3	172	3.95	1210	52.5	95	90	60	3	112	0	2.3	10.2
5/3	173	3.9	1208	52.5	97	92	60	3	125	0	2.1	10.4
5/3	174	3.9	1208	52.5	97	92	60	3	125	0	2.1	10.4
5/3	175	3.9	1208	52.5	97	92	60	3	125	0	2.1	10.4
5/3	176	3.9	1208	52.5	98	93	60	3	120	0	2.3	10.2
5/3	177	3.9	1208	52.5	98	93	60	3	120	0	2.3	10.2
5/3	178	3.9	1208	52.5	98	93	60	3	120	0	2.3	10.2
5/5	179	3.95	1219	52	82	83	60	3.5	119	0	2.2	10.2
5/5	180	3.95	1212	52	83	84	60	3.5	125	0	2.3	10.2
5/5	181	3.95	1210	52	84	85	60	3.5	125	0	2.4	10.2
5/6	182	4	1206	52.5	90	84	60	3.5	115	0	2.3	10.3
5/6	183	3.95	1203	52.5	90	84	60	3.5	115	0	2.4	10.2
5/6	184	3.95	1200	52.5	90	86	60	3.5	115	0	2.3	10.2
5/10	185	4.1	1190	53	93	89	60	3.5	128	0	2.3	10.2
5/10	186	4.1	1185	53	94	90	60	3.5	117	0	2.4	10.1
5/10	187	4.1	1180	52.5	95	87	150	4.9	102	0	2.4	10.1
5/10	188	4.1	1185	52.5	94	89	150	4.5	60	0	2.4	10.1
5/10	189	4.1	1179	52.5	95	89	60	3.5	55	0	2.4	10.1
5/10	190	4.1	1183	52.5	96	88	0	3.5	60	0	2.3	10.2
5/10	191	4.1	1245	50.5	98	91	60	3.5	110	0	1.15	11.1
5/10	192	4.1	1244	50.5	98	89	60	3.5	116	0	1.2	11.1
5/10	193	4.1	1241	50.5	98	91	150	4.9	109	0	1.1	11.2
5/10	194	4.1	1241	50.5	98	89	150	4.5	61	0	1.2	11
5/10	195	4.1	1241	50.5	98	89	60	3.5	65	0	1	11.2
5/10	196	4.1	1241	50.5	98	89	0	3.5	62	0	1	11.2
5/10	197	4.1	1202	52.5	99	89	60	3.5	115	0	2.1	10.3
5/10	198	4.05	1205	52.5	99	89	60	3.5	115	0	2.1	10.3
5/10	199	4.05	1204	52.5	100	89	150	4.5	125	0	2.2	10.3
5/10	200	4.1	1185	56	98	89	60	3.5	120	0	3.5	9.45
5/10	201	4.1	1179	56	98	88	60	3.5	120	0	3.5	9.4
5/10	202	4.1	1175	56	97	88	150	4.9	120	0	3.5	9.45
5/10	203	4.1	1171	56	96	88	150	4.5	59	0	3.6	9.3
5/10	204	4.1	1174	56	95	88	60	3.5	58	0	3.45	9.45
5/10	205	4.1	1175	56	93	87	0	3.5	58	0	3.6	9.3

TABLE B-2. CO BOILER DATA

DATE	TEST NO.	TOTAL AIR LB/HR	STAGE AIR LB/HR	MAIN AIR DP (IWG)	MAIN AIR TEMP F	FUEL FLOW RDG %	FUEL FLOW TEMP F	WINDBX TEMP F	CO GAS TEMP F	STACK TEMP F	GAS COMPOSIT. (DRY) NOX PPM	O2 %	CO PPM	CO2 %	INJ. OOS	INJ. POSIT	INJ. ORIENT	COMMENTS
3/29	1	-	-	.5	91	37.5	93	94	1218	410	130	2.15	50	10.7	0	7	RI	----------
3/29	2	-	-	.5	91	37.5	94	94	1216	411	220	2.1	50	10.7	0	7	RI	----------
3/29	3	-	-	.5	92	37.5	95	95	1214	412	235	2.1	42	10.7	0	7	RI	----------
3/29	4	-	-	.5	93	40	96	97	1228	408	185	2.2	90	10.6	0	7	RI	----------
3/29	5	-	-	.5	93	40	98	97	1230	409	185	2.2	100	10.6	0	7	RI	----------
3/29	6	-	-	.5	93	40	98	97	1229	410	102	2.2	100	10.7	0	7	RI	----------
3/29	7	-	-	.5	94	31.5	97	97	1188	413	128	2.1	25	10.7	0	7	RI	----------
3/29	8	-	-	.5	94	31.5	97	97	1178	414	261	2.1	28	10.7	0	7	RI	----------
3/29	9	-	-	.5	95	30	97	98	1163	416	300	2.1	28	10.7	0	7	RI	----------
3/29	10	-	-	.5	94	25	96	97	1145	415	341	2.12	30	10.6	0	7	RI	----------
3/29	11	-	-	.5	93	24.5	94	96	1136	417	305	2.1	40	10.7	0	7	RI	----------
3/29	12	-	-	.5	94	24.5	94	96	1134	416	120	2.1	40	10.7	0	7	RI	----------
4/8	13	-	-	.7	89	37.5	86	91	1217	393	119	3.5	90	9.6	0	7	RI	----------
4/8	14	-	-	.7	90	37.5	87	92	1215	411	205	3.4	80	9.7	0	7	RI	----------
4/8	15	-	-	.7	90	37.5	88	93	1211	413	245	3.4	70	9.75	0	7	RI	----------
4/8	16	-	-	.7	91	41	89	93	1234	411	190	3.55	135	9.7	0	7	RI	----------
4/8	17	-	-	.7	91	41	90	94	1239	411	185	3.55	135	9.7	0	7	RI	----------
4/8	18	-	-	.7	92	41	91	95	1241	411	110	3.55	155	9.7	0	7	RI	----------
4/8	19	-	-	.7	93	32.5	91	95	1200	417	119	3.56	65	9.75	0	7	RI	----------
4/8	20	-	-	.7	93	32.5	91	96	1190	417	240	3.5	55	9.75	0	7	RI	----------
4/8	21	-	-	.7	93	32.5	92	96	1188	417	260	3.55	60	9.75	0	7	RI	----------
4/8	22	-	-	.7	93	27	92	96	1177	419	305	3.45	59	9.75	0	7	RI	----------
4/8	23	-	-	.7	93	27	92	96	1169	420	278	3.45	40	9.75	0	7	RI	----------
4/8	24	-	-	.7	93	27	92	96	1165	420	112	3.45	42	9.75	0	7	RI	----------
4/11	25	-	-	.45	86	37.5	81	88	1231	405	121	1.55	62	11.0	0	7	RI	----------
4/11	26	-	-	.45	85	37.5	81	88	1232	404	185	1.55	55	11.0	0	7	RI	----------
4/11	27	-	-	.45	85	37.5	82	88	1232	406	195	1.5	65	11.0	0	7	RI	----------
4/11	28	-	-	.45	86	42.5	83	89	1272	402	132	1.4	170	11.1	0	7	RI	----------
4/11	29	-	-	.45	86	42.5	83	89	1268	403	128	1.4	265	11.1	0	7	RI	----------
4/11	30	-	-	.45	86	42.5	83	89	1267	402	90	1.4	180	11.1	0	7	RI	----------
4/11	31	-	-	.45	86	32	81	89	1235	404	-	1.5	39	11	0	7	RI	ABORT
4/11	32	-	-	.45	86	32	82	89	1220	406	250	1.48	35	11	0	7	RI	----------
4/11	33	-	-	.45	86	32	86	89	1211	405	270	1.45	35	11	0	7	RI	----------
4/11	34	-	-	.45	87	27	83	89	1197	406	320	1.47	30	11	0	7	RI	----------
4/11	35	-	-	.45	86	27	82	89	1192	406	293	1.47	30	11	0	7	RI	----------
4/11	36	-	-	.45	86	27	82	89	1190	406	132	1.5	30	11	0	7	RI	----------
4/11	37	-	-	.55	87	37	83	90	1235	408	245	2.25	40	10.6	0	7	RI	----------
4/11	38	-	-	.6	87	37	83	90	1172	433	223	2.25	50	10.7	0	7	RI	----------
4/11	39	-	-	1.22	87	78.5	83	89	1230	491	178	2.3	50	10.6	0	7	RI	----------
4/11	40	-	-	.55	87	37	83	90	1216	408	285	2.16	45	10.6	0	7	RI	----------
4/11	41	-	-	.55	87	37	84	90	1220	408	190	2.25	45	10.6	0	7	RI	----------
4/14	42	-	-	.55	93	38	95	97	1207	407	115	2	45	10.7	0	7	RI	NH3 MEASUREMENTS
4/14	43	-	-	.55	94	57.5	93	97	1212	409	220	2.2	40	10.5	0	7	RI	NH3 MEASUREMENTS
4/14	44	-	-	.55	94	37	92	98	1215	411	243	2.15	45	10.5	0	7	RI	NH3 MEASUREMENTS
4/15	45	-	-	.55	92	41.5	92	96	1256	405	168	2.25	95	10.5	0	7	RI	NH3 MEASURMENTSS
4/15	46	-	-	.55	96	28	94	98	1175	411	295	2.1	35	10.6	0	7	RI	----------
4/18	47	-	-	.55	88	37.5	83	91	1202	375	218	2.2	60	10.5	0	7	RI	----------
4/18	48	-	-	.55	89	37.5	85	92	1201	387	205	2.25	70	10.5	0	7	RI	SWIRL - 1-16=35
4/18	49	-	-	.55	92	37.5	88	95	1196	395	182	2.2	70	10.5	0	7	RI	SWIRL - LEFT=0, RT.=45
4/18	50	-	-	.55	93	37.5	91	96	1192	392	170	2.25	150	10.5	0	7	RI	SWIRL - 1-3, 12-16=0

TABLE B-2. (CONTINUED)

DATE	TEST NO.	TOTAL AIR LB/HR	STAGE AIR LB/HR	MAIN AIR DP (IWG)	MAIN AIR TEMP F	FUEL FLOW RDG %	FUEL FLOW TEMP F	WINDBX TEMP F	CO GAS TEMP F	STACK TEMP F	GAS COMPOSIT. (DRY) NOX PPM	O2 %	CO PPM	CO2 %	INJ. OOS	INJ. POSIT	INJ. ORIENT.	COMMENTS
4/18	51	-	-	.55	94	37.5	93	97	1189	398	180	2.2	92	10.5	0	7	RI	SWIRL = 7-13=0
4/18	52	-	-	.55	95	37.5	95	97	1188	398	175	225	200	10.5	0	7	RI	SWIRL = 1-4, 13-16=0
4/18	53	-	-	.55	94	37.5	95	97	1186	395	178	2.23	103	10.5	0	7	RI	SWIRL = 1,2, 11-16=0
4/18	54	-	-	.55	95	37	95	98	1181	383	215	2.2	50	10.5	1,5-8	7	RI	----------
4/18	55	-	-	.55	96	37	95	99	1185	404	150	2.15	575	10.6	1,5-7	7	RI	----------
4/18	56	-	-	.55	96	37	96	99	1185	400	160	2.15	200	10.6	1,5,6	7	RI	----------
4/18	57	-	-	.55	96	37	97	99	1833	405	198	2.1	55	10.6	1,5	7	RI	----------
4/18	58	-	-	.55	96	37	97	99	1184	403	210	2.2	40	10.6	1	7	RI	----------
4/18	59	-	-	.55	96	37	96	99	1184	408	170	2.2	90	10.6	1-4,8	7	RI	----------
4/18	60	-	-	.55	96	37	97	99	1185	394	140	2.15	205	10.6	1-4	7	RI	----------
4/18	61	-	-	.55	96	37	96	99	1185	400	110	2.2	520	10.6	2-5	7	RI	----------
4/18	62	-	-	.55	95	37	96	98	1184	400	125	2.2	250	10.6	2,3,4	7	RI	----------
4/18	63	-	-	.55	95	37	95	98	1184	400	160	2.15	95	10.6	2,3	7	RI	----------
4/18	64	-	-	.55	95	37	97	98	1185	401	192	2.15	-	10.6	2	7	RI	----------
4/19	65	-	-	.55	96	37	97	99	1188	405	143	2.1	82	10.6	1-3	7	RI	----------
4/19	66	-	-	.55	96	37	97	99	1187	401	109	2.15	450	10.5	3-5	7	RI	----------
4/19	67	-	-	.55	97	37	97	100	1187	402	148	2.15	330	10.5	1-5	7	RI	----------
4/19	68	-	-	.55	97	37	97	100	1188	407	168	2.15	80	10.5	1-3,8	7	RI	----------
4/19	69	-	-	.55	96	37	97	99	1187	400	99	2.1	510	10.5	3-5	7	RI	----------
4/19	70	-	-	.55	96	37	97	99	1187	400	109	2.15	320	10.5	2-4	7	RI	----------
4/19	71	-	-	.55	96	37	97	99	1187	403	207	2.15	40	10.6	0	7	RI	----------
4/19	72	-	-	.55	92	37	90	95	1196	396	218	2.15	50	10.5	0	7	RI	----------
4/19	73	-	-	.55	93	37	91	96	1195	398	170	2.28	130	10.5	0	7	RI	PORTS = 1-8
4/19	74	-	-	.55	93	37	92	96	1191	398	175	2.25	103	10.5	0	7	RI	PORTS = 1,3,5,7
4/19	75	-	-	.55	93	37	93	96	1191	399	207	2.2	55	10.5	0	7	RI	PORTS = 3
4/19	76	-	-	.55	95	37	95	98	1192	404	200	2.2	55	10.5	0	7	RI	PORTS = 3,7
4/19	77	-	-	.55	95	37	95	98	1193	401	195	2.3	60	10.4	0	7	RI	PORTS = 2,3
4/19	78	-	-	.55	95	37	96	99	1195	400	185	2.3	70	10.4	0	7	RI	PORTS = 2-4
4/19	79	-	-	.55	95	37	96	99	1194	404	210	2.2	45	10.5	0	7	RI	PORTS = 7
4/19	80	-	-	.55	96	37	96	99	1196	403	189	2.25	75	10.5	0	7	RI	PORTS = 7,8
4/19	81	-	-	.55	96	37	96	99	1195	403	182	2.25	90	10.5	0	7	RI	PORTS = 6-8
4/19	82	-	-	.55	96	37	96	99	1194	401	205	2.2	60	10.5	0	7	RI	PORTS = 1
4/19	83	-	-	.55	96	37	96	99	1194	401	189	2.3	75	10.4	0	7	RI	PORTS = 1,2
4/19	84	-	-	.55	96	37	95	99	1195	400	178	2.3	135	10.4	0	7	RI	PORTS = 1,2,8
4/19	85	-	-	.55	96	37	95	99	1195	400	175	2.2	100	10.5	0	7	RI	PORTS = 5
4/19	86	-	-	.55	96	37	96	99	1193	400	165	2.25	115	10.5	0	7	RI	PORTS = 4,5
4/19	87	-	-	.55	96	37	96	99	1191	401	165	2.2	115	10.5	0	7	RI	PORTS = 4-6
4/19	88	-	-	.55	97	37	96	100	1189	398	168	2.3	115	10.4	0	7	RI	PORTS = 1-8-1"
4/19	89	-	-	.55	96	37	96	99	1188	403	175	2.2	100	10.5	0	7	RI	PORTS = 1,3,5,7-0.5"
4/19	90	-	-	.55	96	37	97	99	1188	403	185	2.15	83	10.5	0	7	RI	PORTS = 1,3,5,7-0.25"
4/20	91	-	-	.55	85	38	84	88	1211	395	235	2.15	50	10.5	0	5	RI	----------
4/20	92	-	-	.55	87	38	86	89	1208	397	237	2.15	50	10.5	0	5	RI	PORTS = 1,3,5,7
4/20	93	-	-	.55	89	37.5	88	92	1209	409	230	2.2	50	10.5	1,5,6	5	RI	----------
4/20	94	-	-	.55	89	37.5	88	92	1206	401	205	2.2	155	10.5	1,5-7	5	RI	----------
4/20	95	-	-	0	0	0	0	0	0	0	0	0	0	0	2,5	5	RI	UNSTABLE
4/20	96	-	-	.55	89	37	89	92	1208	394	149	2.3	430	10.4	2-5	5	RI	----------
4/20	97	-	-	.55	89	37	89	92	1210	399	180	2.27	85	10.5	2,3	5	RI	----------
4/20	98	-	-	.55	88	37	89	92	1210	402	128	2.2	270	10.5	2-4	5	RI	----------
4/20	99	-	-	.55	88	37	89	91	1208	401	165	2.2	185	10.5	3-5	5	RI	----------
4/20	100	-	-	.55	89	36.5	90	92	1207	407	141	2.3	185	10.5	1-4	5	RI	----------
4/20	101	-	-	.55	89	36.5	90	92	1206	407	148	2.28	190	10.5	1-4	5	RI	----------

TABLE B-2. (CONTINUED)

DATE	TEST NO.	TOTAL AIR LB/HR	STAGE AIR LB/HR	MAIN AIR DP (IWG)	MAIN AIR TEMP F	FUEL FLOW RDG %	FUEL FLOW TEMP F	WINDBX TEMP F	CO GAS TEMP F	STACK TEMP F	GAS COMPOSIT. (DRY) NOX PPM	O2 %	CO PPM	CO2 %	INJ. OOS	INJ. POSIT	INJ. ORIENT.	COMMENTS
4/20	102	-	-	.55	90	37	90	90	1206	413	220	2.2	40	10.6	0	5	PP	----------
4/20	103	-	-	.55	90	37	91	93	1202	411	239	2.25	35	10.5	0	6	PP	----------
4/20	104	-	-	.55	91	37	91	94	1200	419	199	2.1	75	10.6	1,5-8	6	PP	----------
4/20	105	-	-	.55	91	37	91	94	1202	417	230	2.2	53	10.5	1,5-7	6	PP	----------
4/20	106	-	-	.55	91	37	91	94	1200	409	249	2.12	45	10.6	3-5	6	PP	----------
4/20	107	-	-	.55	92	37	91	95	1201	406	240	2.2	40	10.5	1-5	6	PP	----------
4/20	108	-	-	.55	91	37	92	95	1201	403	150	2.25	380	10.5	2-6	6	PP	----------
4/20	109	-	-	.55	91	37	91	94	1200	400	205	2.2	145	10.5	2-6	6	PP	----------
4/20	110	-	-	.55	91	37	91	94	1200	404	180	2.15	165	10.5	4-8	6	PP	----------
4/21	111	-	-	.55	89	38	86	91	1209	394	33	7.12	2.E4	6.6	0	7	RO	SWIRL = 1-16=0
4/21	112	-	-	.55	88	37	87	91	1191	415	102	2.25	470	10.5	0	7	RO	SWIRL = 1,5,9,13=35; OTH=15
4/21	113	-	-	.55	89	37	88	91	1192	417	110	2.29	370	10.4	0	7	RO	SWIRL = ALT. 0,45
4/21	114	-	-	.55	92	37.5	88	95	1188	406	240	2.2	50	10.5	0	7	RI	LOW VELOC. INJECTORS
4/21	115	-	-	.55	92	37	88	95	1189	403	85	2.8	6500	9.9	1,5-8	7	RI	LOW VELOC. INJECTORS
4/21	116	-	-	.55	92	37	88	95	1190	410	139	2.33	800	10.4	1,5-7	7	RI	LOW VELOC. INJECTORS
4/21	117	-	-	.55	92	37	89	95	1189	409	155	1.29	170	10.5	1,5-6	7	RI	LOW VELOC. INJECTORS
4/21	118	-	-	.55	91	37	90	96	1188	408	203	2.2	95	10.5	1,5	7	RI	LOW VELOC. INJECTORS
4/21	119	-	-	.55	93	37	90	96	1188	388	245	2.2	45	10.5	1	7	RI	LOW VELOC. INJECTORS
4/22	120	-	-	.55	90	37	86	93	1182	401	132	2.35	195	10.4	1-4,8	7	RI	LOW VELOC. INJECTORS
4/21	121	-	-	.55	90	37	87	93	1183	397	140	2.25	230	10.5	1-4	7	RI	LOW VELOC. INJECTORS
4/22	122	-	-	.55	91	37	88	94	1182	400	160	2.25	155	10.5	2-4	7	RI	LOW VELOC. INJECTORS
4/22	123	-	-	.55	91	37	88	93	1284	401	93	2.3	1250	10.4	2-5	7	RI	LOW VELOC. INJECTORS
4/22	124	-	-	.55	91	37	89	94	1188	407	225	2.25	60	10.5	2,3	7	RI	LOW VELOC. INJECTORS
4/22	125	-	-	.55	91	37	90	94	1188	409	230	2.15	50	10.6	2	7	RI	LOW VELOC. INJECTORS
4/22	126	-	-	.55	92	37	90	94	1189	406	205	2.25	55	10.5	1-3	7	RI	LOW VELOC. INJECTORS
4/22	127	-	-	.55	92	37	90	95	1186	404	119	2.2	250	10.6	3-5	7	RI	LOW VELOC. INJECTORS
4/22	128	-	-	.55	92	37	91	95	1183	403	120	2.25	390	10.5	3-5	7	RI	LOW VELOC. INJECTORS
4/22	129	-	-	.55	92	37	91	95	1186	404	75	2.35	600	10.5	3-5	7	RI	LOW VELOC. INJECTORS
4/22	130	-	-	.55	92	37	92	95	1185	405	125	2.35	240	10.5	1-5	7	RI	LOW VELOC. INJECTORS
4/22	131	-	-	.55	92	37	92	95	1185	413	180	2.25	50	10.5	1-3,8	7	RI	LOW VELOC. INJECTORS
4/22	132	-	-	.55	93	37	93	96	1185	404	152	2.3	225	10.5	3-5	7	RI	LOW VELOC. INJECTORS, SWIRL = 35
4/22	133	-	-	.55	95	37	95	98	1181	416	190	2.2	60	10.5	0	7	PP	LOW VELOC. INJECTORS
4/22	134	-	-	.55	95	37	95	98	1183	422	150	2.4	400	10.4	1,5-8	6	PP	LOW VELOC. INJECTORS
4/22	135	-	-	.55	95	37	95	98	1186	427	193	2.4	115	10.4	1,5-7	6	PP	LOW VELOC. INJECTORS
4/22	136	-	-	.55	95	38	95	98	1190	415	197	2.3	42	10.5	3-5	6	PP	LOW VELOC. INJECTORS
4/22	137	-	-	.55	94	37.5	94	97	1190	411	180	2.4	60	10.4	1-5	6	PP	LOW VELOC. INJECTORS
4/22	138	-	-	.55	94	37	93	97	1191	411	225	2.4	65	10.4	2-6	6	PP	LOW VELOC. INJECTORS
4/22	139	-	-	.55	95	37.5	94	97	1189	422	135	2.3	1950	10.4	4-8	6	PP	LOW VELOC. INJECTORS
4/22	140	-	-	.55	95	37	94	97	1189	423	160	2.35	90	10.4	1,2,6-8	6	PP	LOW VELOC. INJECTORS
4/22	141	-	-	.55	95	38	94	98	1190	425	142	2.3	125	10.5	1-3,7,8	6	PP	LOW VELOC. INJECTORS
4/22	142	-	-	.55	96	38	94	98	1190	422	149	2.3	100	10.5	1-4,8	6	PP	LOW VELOC. INJECTORS
4/25	143	1118	314	.55	93	39.5	91	96	1187	420	62	2.6	315	10.2	0	7	PP	AIR FLOWS NG
4/25	144	1118	251	.55	94	39.5	92	96	1187	420	113	2.9	90	10	0	7	RI	AIR FLOWS NG
4/27	145	1118	134	.55	89	39.5	86	91	1176	415	151	2.65	50	10.2	0	7	RI	----------
4/27	146	1118	250	.55	89	39.5	88	92	1175	421	100	2.7	60	10.2	0	7	RI	----------
4/27	147	1118	300	.55	91	39.5	90	93	1174	421	70	2.65	180	10.2	0	7	RI	----------
4/27	148	1118	0	.55	92	39.5	92	94	1175	422	170	1.95	40	10.7	0	7	RI	----------
4/27	149	1118	0	.55	92	38	93	94	1174	422	178	2.2	45	10.5	0	7	RI	----------
4/27	150	-	-	.55	92	38	93	95	1174	422	158	2.25	85	10.5	0	7	RI	PORTS = 1,3,5,7

TABLE B-2. (CONTINUED)

DATE	TEST NO.	TOTAL AIR LB/HR	STAGE AIR LB/HR	MAIN AIR DP (IWG)	MAIN AIR TEMP F	FUEL RDG %	FUEL FLOW TEMP F	WINDBX TEMP F	CO GAS TEMP F	STACK TEMP F	GAS COMPOSIT. (DRY) NOX PPM	O2 %	CO PPM	CO2 %	INJ. QOS	INJ. POSIT	INJ. ORIENT.	COMMENTS
4/27	151	-	-	.55	92	38	93	95	1173	424	158	2.3	115	10.4	0	7	RI	PORTS = 1-8
4/27	152	1118	0	.55	95	37.5	95	97	1179	429	177	2.15	55	10.6	0	7	RI	----------
4/27	153	1118	95	.55	95	37.5	95	97	1179	429	162	2.3	58	10.5	0	7	RI	AIR LANCE = 2'
4/27	154	1118	95	.55	95	37.5	95	97	1179	429	161	2.29	55	10.5	0	7	RI	AIR LANCE = 3'
4/27	155	1118	95	.55	95	37.5	95	97	1179	429	170	2.2	55	10.6	0	7	RI	AIR LANCE = 4'
5/2	156	-	-	.55	90	38	87	92	1193	392	198	2.1	75	10.5	0	7	RI	INJECTORS 1,3,5,7 TO PORTS
5/2	157	-	-	.55	91	38	88	93	1191	402	190	2.15	85	10.5	0	7	RI	----------
5/2	158	-	-	.55	91	38	89	94	1194	411	210	2.15	55	10.5	0	7	RI	FUEL TO CO GAS: 25%
5/2	159	-	-	.55	91	38	90	94	1196	417	225	2.1	55	10.5	0	7	RI	FUEL TO CO GAS: 50%
5/2	160	-	-	.55	91	38	91	94	1192	418	225	2.1	55	10.5	0	7	RI	FUEL TO CO GAS: 75%
5/2	161	-	-	.55	92	38	92	95	1186	418	220	2.2	55	10.5	0	7	RI	FUEL TO CO GAS:100%
5/2	162	1118	95	.55	94	38	94	97	1195	415	151	2.6	400	10.3	0	7	RI	AIR LANCE = 2' (NC)
5/2	163	1118	95	.55	94	38	94	97	1195	415	168	2.4	200	10.4	0	7	RI	AIR LANCE = 3' (NC)
5/2	164	1118	95	.55	94	38	94	97	1195	415	210	2.5	65	10.4	0	7	RI	AIR LANCE = 0' (NC)
5/2	165	1118	232	.6	94	38	94	97	1189	412	109	.7	125	11.3	0	7	RI	AIR LANCE = 14.5" (NC)
5/2	166	1118	189	.55	95	38	95	98	1188	411	115	1.05	175	11.1	0	7	RI	AIR LANCE = 14.5" (NC)
5/3	167	1118	232	.55	92	37.5	90	95	1179	399	100	3.1	400	9.9	2-4	7	RI	----------
5/3	168	1118	232	.55	93	38	91	95	1175	405	113	2	150	10	0	7	RI	----------
5/3	169	1118	134	.55	96	38	96	98	1179	415	188	2.3	60	10.4	0	7	RI	----------
5/3	170	895	173	.35	97	38	97	99	1168	414	106	2.25	500	10.5	0	7	RI	AIR LANCE = 15.5"
5/3	171	895	173	.35	97	38	97	99	1168	414	100	2.22	440	10.5	0	7	RI	AIR LANCE = 21.5"
5/3	172	895	173	.35	97	38	97	99	1168	414	88	2.2	825	10.5	0	7	RI	AIR LANCE = 27.5"
5/3	173	1015	98	.45	99	37.5	99	102	1165	420	135	2.5	300	10.3	0	7	RI	AIR LANCE = 21.5"
5/3	174	1015	98	.45	99	37.5	99	102	1165	420	130	2.4	300	10.3	0	7	RI	AIR LANCE = 27.5"
5/3	175	1015	98	.45	99	37.5	99	102	1165	420	145	2.45	320	10.3	0	7	RI	AIR LANCE = 15.5"
5/3	176	1070	39	.5	100	37.5	100	102	1165	414	155	2.3	290	10.4	0	7	RI	AIR LANCE = 15.5"
5/3	177	1070	39	.5	100	37.5	100	102	1165	414	150	2.35	380	10.4	0	7	RI	AIR LANCE = 21.5"
5/3	178	1070	39	.5	100	37.5	100	102	1165	414	160	2.25	160	10.5	0	7	RI	AIR LANCE = 27.5"
5/5	179	-	-	.55	90	37.5	83	92	1172	412	151	2.02	120	10.4	2-4	M	RI	LONG DIVERGENT THROAT
5/5	180	-	-	.55	90	37.5	83	92	1163	412	165	2.03	100	10.5	2-4	7	RI	LONG DIVERGENT THROAT
5/5	181	-	-	.55	90	37.5	84	92	1162	410	220	1.9	55	10.6	0	7	RI	LONG DIVERGENT THROAT
5/6	182	-	-	.55	92	37.5	90	95	1161	399	170	2.3	230	10.4	2-4	7	RI	LONG STRAIGHT THROAT
5/6	183	-	-	.55	92	37.5	91	95	1157	401	198	2.25	80	10.4	2-4	M	RI	LONG STRAIGHT THROAT
5/6	184	-	-	.55	93	37.5	92	95	1155	407	235	2.2	50	10.5	0	7	RI	LONG STRAIGHT THROAT
5/10	185	-	-	.55	94	39	92	95	1149	411	205	2.35	60	10.4	0	7	RI	----------
5/10	186	-	-	.55	94	39.5	94	97	1144	407	129	2.35	400	10.4	3-5	7	RI	----------
5/10	187	-	-	.55	95	39.5	96	97	1140	409	135	2.35	630	10.4	3-5	7	RI	----------
5/10	188	-	-	.55	95	39.5	96	97	1142	409	135	2.35	550	10.4	3-5	7	RI	----------
5/10	189	-	-	.55	96	39.5	97	98	1139	411	110	2.39	600	10.4	3-5	7	RI	----------
5/10	190	-	-	.55	96	39.5	97	98	1141	408	40	2.4	2250	10.3	3-5	7	RI	----------
5/10	191	-	-	.55	97	44.5	99	99	1196	414	170	2.4	70	10.4	0	7	RI	----------
5/10	192	-	-	.55	97	44.5	99	99	1193	408	103	2.5	930	10.3	3-5	7	RI	----------
5/10	193	-	-	.55	97	44.5	99	99	1191	409	99	2.5	1800	10.3	3-5	7	RI	----------
5/10	194	-	-	.55	97	44.5	99	99	1190	406	95	2.45	1890	10.3	3-5	7	RI	----------
5/10	195	-	-	.55	98	44.5	99	100	1187	408	89	2.5	1800	10.3	3-5	7	RI	----------
5/10	196	-	-	.55	98	44.5	100	100	1192	407	31	2.7	4000	10.1	3-5	7	RI	----------
5/10	197	-	-	.8	98	57	100	101	1155	449	178	2.2	40	10.5	0	7	RI	----------
5/10	198	-	-	.8	98	57.5	100	100	1158	438	135	2.25	125	10.5	3-5	7	RI	----------
5/10	199	-	-	.8	98	57.5	101	101	1159	446	169	2.2	120	10.5	3-5	7	RI	----------
5/10	200	-	-	.55	99	32.5	100	102	1141	419	260	2.2	55	10.5	0	7	RI	----------
5/10	201	-	-	.55	99	32.5	99	101	1137	416	200	2.2	80	10.5	3-5	7	RI	----------
5/10	202	-	-	.55	98	32.5	99	101	1133	415	269	2.25	90	10.5	3-5	7	RI	----------
5/10	203	-	-	.55	98	32.5	98	100	1130	414	250	2.2	85	10.5	3-5	7	RI	----------
5/10	204	-	-	.55	97	32.5	97	100	1131	413	175	2.35	110	10.4	3-5	7	RI	----------
5/10	205	-	-	.55	97	32.5	96	99	1133	413	50	2.35	220	10.4	3-5	7	RI	----------

APPENDIX C

CALCULATION OF VOLUMETRIC RATIO OF CO-GAS TO STACK GAS

For each test the volumetric ratio of CO-gas to stack gas, R, was calculated. This ratio was used to convert NO_x and ammonia concentrations in the CO-gas to a stack basis (i.e., diluted by burner combustion products). This conversion was necessary in order to calculate net NO_x formation in the CO boiler (see Equation 1 in Section 6), and was also used to calculate ammonia conversion to NO_x and survival rate of NO_x entering with the CO-gas.

$$R = V_R/V_S \qquad \text{(C-1)}$$

$$V_R = W_R \times (1 - M_R)/MW_R$$

$$V_S = W_S \times (1 - M_S)/MW_S$$

where

R = volumetric ratio of CO-gas to stack gas (dry basis)
V = volumetric flow (dry)
W = mass flow (wet)
M = moisture content (mass fraction)
MW = molecular weight (dry)
Subscript R denotes CO-gas (Regenerator effluent)
Subscript S denotes stack gas

The wet mass flow rates were calculated using the equations in Appendix A. ($W_R = W_2$ and $W_S = W_2 + W_4 + W_5$). Moisture content and dry molecular weight of the CO-gas were calculated from CO content using equations based on equilibrium predictions (Table 2 in Section 6). Moisture content and dry molecular weight of stack gas were calculated from O_2 content using equations for natural gas combustion products.

APPENDIX D

CORRECTION FOR VARIATIONS IN CO-GAS NO_x LEVEL

The following equations were used to correct all net NO_x^N values to a constant (120 ppm) CO-gas NO_x^R level.

$$NO_x^{NC} = NO_x^N + (120 - NO_x^R) * (s - 1) * R \qquad (D\text{-}1)$$

where

NO_x^{NC} = net NO_x formed in CO boiler, ppm (dry), corrected to 120 ppm NO_x^R

NO_x^N = net NO_x formed in CO boiler, ppm (dry)

NO_x^R = NO_x measured in CO-gas, ppm (dry)

s = approximate survival rate of NO_x^R in passing through CO boiler

R = volumetric ratio of CO-gas to total stack gas (dry)

The regenerator NO_x survival rate was found to be approximately 0.77 under unstaged conditions (NO_x levels ~210 ppm) and approximately 0.38 where staging was sufficiently effective to produce substantial reductions in NO_x (NO_x levels ~100 ppm). Accordingly, for nominal regenerator ammonia levels, the survival rate could be reasonably estimated as:

$$s = 0.77 + 0.00336 * (NO_x^S - 210)$$

where

NO_x^S = NO_x measured in stack, ppm (dry, corrected to 3% O_2)

For tests in which the regenerator ammonia was perturbated, the survival rate was assigned either 0.77 or 0.38 depending on whether the test involved effective staging.

END

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